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Various Factors of Pressure-Driven Entry of Soil Gas into a Detached House Through Concrete Foundation

Measurements, Statistical Analysis and Crawl Space Modelling

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Summary

The effect of different factors on indoor radon

The impact of physical and meteorological factors on the rate of radon entry into a building were examined using linear regression analysis in seven houses with mechanical supply and exhaust ventilation. Explanatory factors were the indoor-outdoor pressure difference, the indoor-outdoor temperature difference, the wind direction and speed and, in two cases, changes in barometric pressure and rain. The coefficient of determination of the measured factors was not very high because the concentration and movement of radon in the soil is affected by several other factors. In the correlation analyses between pairs of variables at each site, the strength of the radon entry rate correlated strongly with both the indoor-outdoor temperature and pressure differences. Wind speed and direction also affected the radon entry rate in all the houses. In the case of houses which were built on a permeable esker, wind from certain directions increased radon entry. The highest coefficient of determination of indoor radon were found when the wind was perpendicular to the esker.

Changes in barometric pressure were examined using regression analysis, while the effect of rain was examined by covariance analysis in two houses, both with ground-supported concrete slab foundations. The change in atmospheric pressure was not a significant explanatory factor in these houses. According to the results, rain did not influence short-term variations in radon source strength in the houses.

Radon mitigation by ventilation and pressure differences in supply and exhaust ventilated houses

Ventilation reduced radon concentrations effectively in all the houses examined, although this varied at each site. The supply and exhaust ventilation systems in the houses operated in accordance with the design guidelines at the time of construction, and produced a slight overpressure in the living spaces where there were supply air vents. The pressure difference was regulated without any technical faults by the pressure controlled mechanical ventilation of the houses. The usability of the pressure control

system was, however, restricted by the poor airtightness of the buildings. Thus, in non-airtight buildings, a fairly large difference in the supply and exhaust air volumes did not achieve desired changes in the pressure difference.

In two of the houses, the operation of the supply and exhaust ventilation systems and the air currents between the rooms were examined by using the perfluorocarbon tracer gas method (PFT method), and by measuring air volumes. According to the results of these measurements, about 40 - 65% of the supply air in the depressurised bathrooms came as air currents from the living areas, and the remainder came from leakage air from outside. The research confirmed previous findings that mechanical supply and exhaust ventilation works most effectively in airtight houses.

Studies on, and modelling of, crawl spaces

One case study involved a study of the microbiological, radon and VOC conditions in the crawl space and in the living spaces of a detached house before and after changes to the ventilation system. A crawl space pressurisation system using exhaust air from indoors was successful in preventing the convective flow of radon from the soil. However, the warm moist air that was blown into the crawl space produced favourable conditions for microbial growth, and increased concentrations of microbes were detected there.

Separate, carefully-balanced, two-way ventilation in the crawl space, combined with mechanical supply and exhaust ventilation in the living space and an airtight slab between them appeared to be beneficial in preventing air from the crawl space infiltrating into the living space. However, the air change rate in the underpressurised crawl space (relative to indoors) was high in both winter and summer conditions.

Theoretically, a microbiologically safe crawl space was determined with a hygrothermal simulation utilizing the Finnish mould growth model. A simulation of a two-year period included a study of the temperature and humidity conditions as well as mould sensitivity in both open and closed ground structures of crawl spaces. As a new approach, in the mould model, depressurisation (-10 Pa) of the crawl space was used in the calculation of conditions for the mould model.

An open base of uncovered ground (gravel) in the crawl space of the first structure is air-permeable gravel. Two simulations were carried out using typical gravel permeability values (1×10^{-8} (m^2) and 1×10^{-9} (m^2)). In the second simulation the ground in the crawl space was covered with four different materials (concrete, concrete+XPS, XPS and a plastic vapour barrier). It was assumed that these would prevent convective airflow via the ground and decrease the evaporation of moisture.

The simulation showed that a crawl space with an uncovered ground base (gravel) can be kept depressurised with moderate exhaust air ventilation when the soil's permeability value is either $1x10^{-8}$ (m^2) or $1x10^{-9}$ (m^2).

No mould growth was simulated in the examined structures with different air change rate values when the building material's mould growth sensitivity was estimated to be class 3 (medium resistant; concrete, etc.). An open uncovered gravel base is only a functional solution for a crawl space when there are no organic materials. Gravel permeability of $1x10^{-8}$ (m^2) can be regarded as an effective alternative to an open base structure.

When the mould growth sensitivity was set to the class 1 level (very sensitive: pine wood, etc.) as it is for air-sealed covered ground, the recommended ground structure is concrete + insulation with an air change rate of 0.2 to 1 h^{-1} for exhaust air. The simulation showed that a concrete ground structure with an air change rate of 0.2 to 0.6 h^{-1} was also very effective. Concrete structures have the lowest mould-risk index due to concrete's moisture absorption capacity, but the Mould index rises if the air change rate is above the recommended level. The simulation showed that XPS insulation and ground covered with a plastic vapour barrier were not suitable due to their high Mould index.

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Kuopio, the 23th of November, 2018

Timo Keskikuru

Abbreviations and definitions

ΔP_{stack}	pressure difference from stack effect	(Pa)
ΔP_{tot}	total pressure difference	(Pa)
ΔP_{umv}	pressure difference from unbalanced ventilation	(Pa)
ΔP_{w}	pressure difference from wind	(Pa)
ΔT	difference in indoor-outdoor temperature	(^{o}C)
λ_{Rn}	radon radioactive decay constant = 2.1×10^{-6}	(s^{-1})
D	radon diffusion coefficient	($m^2\ s^{-1}$)
λ_{v}	house total ventilation rate	(h^{-1})
λ_{bmv}	mechanical ventilation rate	(h^{-1})
μ	soil gas viscosity	(Pa s)
ρ_{out}	outdoor air density	(kg m^{-3})
AP	barometric pressure	(Pa)
C_s	soil gas radon concentration	(Bq m^{-3})
g	standard acceleration due to earth's gravity	(m s^{-2})
k	flow factor	($m^3\ s^{-1}\ Pa^{-n}$)
k_s	soil permeability	(m^2)
n	flow exponent	(-)
$n_{50\ Pa}$	airtightness, air change rate at 50 Pa	(h^{-1})
p	p-value	(-)
PD_{in-as}	difference in indoor-attic space pressure	(Pa)
PD_{in-out}	difference in indoor-outdoor pressure	(Pa)
Q	infiltration air flow	($m^3\ s^{-1}$)
Q_{bmv}	mechanical ventilation	($m^3\ s^{-1}$)
Q_p	flow rate of mechanical exhaust	($m^3\ s^{-1}$)
Q_s	infiltration air flow rate due to the stack effect	($m^3\ s^{-1}$)
Q_{soil}	flow rate of soil gas	($m^3\ s^{-1}$)
Q_{umv}	infiltration air flow rate due to unbalanced ventilation	($m^3\ s^{-1}$)
Q_t	flow rate of mechanical supply	($m^3\ s^{-1}$)
Q_w	infiltration air flow rate due to the wind effect	($m^3\ s^{-1}$)
$Q_{50\ Pa}$	air flow at 50 Pa	(m^3h^{-1})

R_b	flow resistance of the slab gap	(Pa s m^{-3})
Rn_i	indoor radon concentration	(Bq m^{-3})
Rn_o	outdoor radon concentration	(Bq m^{-3})
R_{soil}	flow resistance of the soil	(Pa s m^{-3})
S_d	rate of radon entry, diffusive radon source	(Bq m^{-3} s^{-1})
S_f	rate of radon entry, convective radon source	(Bq m^{-3} s^{-1})
S_f	rate of radon entry, total	(Bq m^{-3} s^{-1})
T_{in}	indoor temperature	(°C)
T_{out}	outdoor temperature	(°C)
V	volume	(m^3)
Wd	wind direction	(1-8)
Ws	wind speed	(m s^{-1})
z_n	neutral pressure level	(m)
% RH	relative humidity	(%)
M	Mould index	(-)

List of original publications

This thesis is based on the following publications, referred to in the text by their Roman numerals.

I. Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P. Variation of radon entry rate into two detached houses. Atmospheric Environment, 34, 4819-4828, 2000.

II. Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P. Effect of various factors on the radon entry rate into two different types of houses. Building and Environment, 36/10, 1091-1098, 2001.

III. Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P. How did wind affect the radon entry into seven detached houses. In: Proceedings of Radon in the Living Environment 19-23, 309-319, 1999.

IV. Keskikuru, T., Kokotti, H. and Kalliokoski, P. Pressure differences in seven supply and exhaust ventilated houses. Proceedings of Healthy Buildings 2000, 3, 91-97, 2000.

V. Keskikuru, T., Salo, J., Huttunen, P., Kokotti, H., Hyttinen, M., Halonen, R. and Vinha, J. Radon, fungal spores and MVOC reduction in crawl space house: A case study and crawl space development by hygrothermal modelling. Building and Environment, 138, 1-10, 2018.

The disputant is the leading writer for all the above publications. The publications have been produced in collaboration with other scientists at the University of Eastern Finland (Publications I-IV) and at Tampere University of Technology (Publication V) and Ramboll, Finland Ltd. (Publication V). For Publications I – IV the disputant mainly planned the measuring system for the building study, participated in the measurements in the houses, and performed data analysis. The time-dependent hygrothermal modelling (Publication V) was carried out by the scientists at Tampere University of Technology.

Additional unpublished data are also included in the thesis.

Content

1 Introduction

Radon (^{222}Rn) is a radioactive, colourless and odourless noble gas that is produced in the earth as a natural by-product of radium decay (^{226}Ra). The products of radon gas decay are solid, and include the short-lived radon progeny: polonium (^{218}Po and ^{214}Po), bismuth (^{214}Bi) and lead (^{214}Pb). The harmfulness of radon in ambient air arises mainly from ^{218}Po and ^{214}Po, intermediate decay products of radon that emit high-energy alpha particles which, if inhaled, remain in the lungs and damage the bronchial tracts and alveoli. The International Commission on Radiological Protection's (ICRP) values were used in assessing the risk of lung cancer. These are based on epidemiological studies carried out on miners. These epidemiological studies have shown that long-term exposure to radon increases the risk of lung cancer (Lubin, et al., 1995). Two major controlled case studies which examined the links between radon and lung cancer were completed in Finland in 1996 (Auvinen et al., 1996 and Ruosteenoja et al., 1996). According to these studies, it is likely that about 200 cases of lung cancer are caused by radon every a year in Finland. This result corresponds to the results of international pooled analyses (Lubin et al., 1997). The results are also consistent with a Swedish study in the pooled analysis (Pershagen et al., 1994). Although a study in eastern Uusimaa did not find any statistically significant link between radon and lung cancer (Ruosteenoja et al., 1996), other studies (Lubin et al., 1997; Pershagen et al., 1994) have shown that there is a link between radon and lung cancer.

Data from European control studies on the link between residential radon and lung cancer provide direct evidence of a statistically significant association between the two, as predicted by extrapolation from the miner studies (Darby et al., 2005). The dose-response relationship appeared linear with no evidence of a threshold, and there was still a significant relationship among those cases where the measured radon concentrations were below 200 Bq m^{-3}. After stratification of the study for age, sex, region of residence and smoking, the risk of lung cancer per 100 Bq m^{-3} in measured radon concentrations increased by 8.4% (95 % CI = 3.0 %-15.8 %, P = 0.0007). After correction for random uncertainties in the measurement of radon concentrations, the dose-response relation remained linear but nearly doubled in strength to 16 % (95 % CI = 5 %-31 %) per 100 Bq m^{-3} of estimated mean usual radon concentrations. In Europe, radon in the home accounts for about 9 % of deaths from lung cancer and 2 % of all deaths from cancer (Darby et al., 2005).

Mäkeläinen et al (2005) took a risk estimate from a recent European collaborative study and applied it in a Finnish context using national demographics for smoking and radon exposure data. The risk model was simplified from the BEIR VI model, with constant excess relative risk per radon exposure for both sexes, and across different age groups and exposure periods. The estimated annual number of lung cancer deaths in Finland attributable to indoor radon was 354 in a sample based on Radon in Finnish dwellings (Mäkeläinen et al., 2006), and a further study estimated the annual number of lung cancer deaths at 275 (Mäkeläinen et al., 2010).

According to decision 944/92 of the Finnish Ministry of Social Affairs and Health, the radon concentration in indoor air in dwellings should not exceed 400 becquerels per cubic metre (Bq m^{-3}). New dwellings must now be designed and built so that the expected radon concentration does not exceed 200 Bq m^{-3}.

The entry of radon-bearing soil air and infiltration into a dwelling can be affected by physical and meteorological factors. Indoor radon concentration is the result of two factors; convective flows and diffusion from the building's structures. The most significant source of radon is through the surface of the soil under the building, where radon-bearing air from pores in the soil is transferred into the building by convection. Part of the indoor radon levels can also be attributed to diffusion from the soil through the building structures, and from building materials containing radon. The infiltration of radon-bearing soil air and the radon concentration are, of course, affected by the radon concentration in the soil where the building is located. Soil-related factors such as the permeability of the soil and its moisture content may promote the flow of radon. The most important factor that affects radon flows is the type and tightness of the foundations of the building (Arvela et al., 2014).

Radon in indoor air originates from sub-floor airflow and is an indicator of the movement of other gaseous and, to a certain extent, solid impurities from the soil into the indoor air. Due to the favourable temperature and relative humidity conditions, microbial growth is found to be very common in soil infill layers and the average concentration of the detected microbes was high. Fungal or bacterial growth in general was detected in 98 % of the infill soil samples taken from beneath the ground slabs of heated buildings (Rantala et al., 2008). Therefore, soil air infiltration through the sub-floor has to be prevented. The passage of solid particulate pollutants such as fungal spores, leaking from the soil structure into the house is a much more complex and less well-known phenomenon than the passage of gaseous pollutants. In addition to spores produced by microbial flora, organic compounds from metabolic processes are released into the ambient air either directly from vegetation on the surface or from within a damaged structure. The volatile organic compounds from these moulds are known to be unpleasant and, in combination with other indoor air factors, may cause irritation and other symptoms of ill health for residents of the building (Mølhave, 2003; Helalth Canada, 1995; Godish, 2000). The normal indoor concentrations of voltaic organic compounds and microbial organic compounds cannot account for all the reported health complaints in office and residential buildings (Korpi, et al., 1999; Wolkoff and Nielsen, 2001).

Convective radon flow increases with both interior depressurisation and with more air leaking through from the sub-floor. According to physical models, a pressure difference across the sub-floor slab is affected by the indoor-outdoor pressure difference so that, as the depressurisation of the building increases, the pressure difference across the slab also increases. Typically, there is a continuous variation in the indoor-outdoor pressure difference. The pressure difference is caused by the difference in density of the inside and the outdoor air mass, by wind, and by an imbalance between mechanical ventilation flow rates (Kalamees, et al., 2008; Arvela et al., 2014; Kokotti and Kalliokoski, 1992).

Depressurisation, for its part, increases the amount of leakage air through the wall and ceiling structures and dilutes the radon concentration in the indoor air. Wind can also directly affect the pressure difference across the sub-floor slab by forming a pressure field in the immediate vicinity of a building, or the impact of the wind on the soil can extend from farther off. Wind can also reduce the radon concentration in the soil by ventilating the soil. If the building is located in an area of eskers, the flow of soil air is also affected by several factors in addition to the wind, such as the location of the esker, the season, and the esker’s internal convective flows. Wind in esker areas can generate air flows in the soil air inside the eskers which can either prevent or promote convective flows in the soil and also affect the ventilation of the soil in the immediate vicinity of the building (Arvela et al., 1994 and 1988).

When estimating changes in the concentration of radon in the soil, airflows and pressure differences are not included in the most commonly used radon concentration calculation models, which means that soil factors cannot be predicted very accurately with these models. Soil radon concentration is influenced by several factors and, therefore, the indoor air radon concentrations may vary considerably over a short period of time (Arvela et al., 2015).

Radon concentration can be reduced by ventilation and with various technical building solutions. The percentage decrease in radon concentrations varies case by case according to the methods used. Measures to improve ventilation in houses include the efficient use of mechanical and airflow-adjusted ventilation. Other possible measures to reduce radon concentrations are to make structures airtight and to depressurise the building foundation using radon well solutions. Mitigation measures using depressurisation of the building foundation and a radon well have produced good results. Radon mitigation using a supply and exhaust ventilation system has achieved greater reductions in concentrations than just using mechanical exhaust ventilation. Mechanical exhaust ventilation in an airtight house causes depressurisation which can increase radon flows through leaks in the structures into interior rooms, and thus reduces the benefits of the ventilation. Compared with mechanical exhaust ventilation, the use of supply and exhaust ventilation enables the ventilation to reduce depressurisation in the building. Then, radon concentrations are reduced both through increased dilution of the air in the rooms as the ventilation increases, and by reducing infiltration through management of the pressure difference. The pressure difference produced by a supply and exhaust ventilation system is not, however, as clear as in a mechanical exhaust system. According to research by the Radiation and Nuclear Safety Authority, air change is, on average, higher in houses with mechanised ventilation than it is in houses built in the same way but with natural ventilation. Nevertheless, the average radon concentration is slightly higher in houses with mechanised ventilation. Our results indicate that it is important that ventilation is correctly implemented technically, and radon concentration levels are sometimes brought down to recommended levels by the continuous, efficient use of ventilation (Arvela et al., 2012). The best results obtained from ventilation occurred in buildings where the ventilation had hitherto been ineffective, or depressurisation had been too high (Kokotti et al., 1994b: Hoving et al., 1989; Arvela et al., 2010).

Sub-floors with a crawl space have been found to be an effective solution for dealing with radon. However, this requires a well-ventilated crawl space and a good, airtight sub-floor. In the low crawl spaces built today, however, natural ventilation is often insufficient. Mechanical exhaust ventilation can compensate for this, but the infiltration of humid outdoor air is also a source of dampness at certain times of the year. High levels of humidity in crawl spaces have generally been regarded as encouraging microbial growth on structures and surfaces. Because there is always organic material and dust collected on surfaces in a crawl space, these nourishing conditions are favourable for the start of microbial growth. Therefore, the prevailing weather conditions can make a degree of mould growth in crawl spaces unavoidable.

Indoor microbial exposure has been related to adverse health effects such as breathing disorders (wheezing, cough, asthma) and upper respiratory tract symptoms (nasal and throat infections) (Bush et al., 2006; Bernstein et al., 2008; WHO Guidelines, 2009; Mendell et al., 2011).

According to previous studies (Henschel, 1992; Airaksinen et al., 2004a and 2004b; Airaksinen; Nazaroff and Doyle, 1985), some of the air infiltrating a building travels via the crawl space. Crawl space air often contains radon and other contaminants released from the soil and from the crawl space structures and surfaces. Sub-floor leaks and depressurisation in the building increase the infiltration of air from the crawl space into the house. In older buildings, natural ventilation has been relied on to remove humidity and contaminants from the crawl space. However, in newer buildings, mechanical ventilation of exhaust air is more common. Mechanical ventilation has also been used to keep the crawl space depressurised in relation to the living areas in order to reduce air flows from the crawl space into the living space, although it is often difficult to achieve sufficient depressurisation in this way.

2 Literature review

2.1 Radon generation, transport and entry

Radon enters into dwellings from the soil or rock under the dwelling and from the building construction materials. Because radon is slightly soluble in water, radon can also occur in ground water and water supplies. Radon is released continuously into the atmosphere in small amounts, so small concentrations can be detected indoors. Radon generation, its concentration, its transport and its entry inside a building depend on several parameters, most of which are time-dependent. The complexity of this process has led to many theoretical calculations, experimental studies and more recently dynamic modelling to describe the transportation of non-stationary radon. The entry of soil radon into a building is due to the combination of pressure-driven and diffusive flows through joints and cracks in the building's structure that are in contact with the ground.

2.1.1 Diffusive radon entry

Part of the radon concentration in living areas is due to diffusion from building structures containing radon and diffusion from the soil through these structures. The radon generation of a building material depends on the concentration of radium in the material; radon being generated mainly by mineral-based construction materials. Radon diffusion obeys Fick's law in that it is directly proportional to the concentration gradient and the diffusion coefficient of the surrounding material (Nazaroff et al., 1988). The diffusion is the process of transporting matter caused by the concentration gradient. For radon gas it is necessary to take into account the decay constant of radon which can be expressed as a time-dependent equation (Rovenska and Jiránek, 2011).

$$\frac{\partial}{\partial \mathrm{X}}\left(\mathrm{D}\frac{\partial \mathrm{C}}{\partial \mathrm{x}}\right) - \lambda_{\mathrm{Rn}}\,\mathrm{C} = \frac{\partial \mathrm{C}}{\partial \mathrm{t}} \quad , \qquad \textbf{(1)}$$

where D = radon diffusion coefficient ($m^2\ s^{-1}$)
x = distance from the surface exposed to radon (m)
C = radon concentration in the sample ($Bq\ m^{-3}$)
λ_{Rn} = radon radioactive decay constant (s^{-1})
t = time (s)

Diffusive radon entry is driven by the permanent radon concentration gradient in the soil, a consequence of the difference between the radon concentration gradient in the soil and finally the radon diffusion coefficient of the building structures that are in contact with the ground. According to Albarracín's steady-state radon transport model (TRANSRAD), the most relevant soil parameters affecting the radon flux at the top of a crack are: the effective diffusion coefficient, soil gas-permeability and the concentration of radon deep in the soil. When the soil gas-permeability is higher than 3×10^{-12} m^2, convective entry into the house is the dominant entry mechanism, but when the effective diffusion coefficient is higher than 7×10^{-7} $m^2 s^{-1}$, diffusive entry dominates. This means that, even though convective entry is the most important radon entry mechanism, especially for high radon entry rates, diffusive entry should not be neglected (Albarracín et al., 2002).

Soil can be treated as a porous medium consisting of organic matter, grains of soil and pores filled with water and soil gas. Radon is generated from the radioactive decay of the radium which is fixed in the soil grains. Only a fraction of the radon generated in soil ever leaves the solid grain end enters the pores in the soil. The fraction of radon atoms generated in the soil grains that reach the pore volume is known as the emanation coefficient. The definition of the emanation coefficient is the fraction of radon atoms generated that reach the pore volume. The emanation coefficient depends on the radium content, the size and distribution of the soil grains, and the soil's porosity and water content. The soil water content affects the soil radon concentration mainly through its influence on the radon emanation coefficient in the soil. The emanation coefficient increases in line with the water content. For the most common types of soil, the emanation coefficient reaches its maximum when the water content is about 5%. In gravel, radon emanation reaches its maximum at about 1–2% water content, which is when the internal pores within the grains fill up. In clay, the specific grain surface areas are rather high, so a relatively high water content of 10–15% is needed to cover all the surface of the grain (Markkanen and Arvela, 1992).

The total soil porosity is defined as the ratio of the volume of air and water in the soil pores to the total soil volume. Obviously, a higher total soil porosity affords more opportunity for the radon to escape from the grain surface, which then leads to a higher radon concentration in the soil (Sun K et al., 2004).

The radon generation of different building materials can be assessed by measuring the radium concentration (Bq kg^{-1}) in samples of the material in order to determine its radon generation values. The measurement of the radium concentration in building materials is carried out in a laboratory. The basic principles of radon generation in building materials are the same as in soil. The most important difference between building materials and soil is that the water content of building materials is lower and does not change over time as quickly as it does in soil. The primary radon transport mechanism in materials is diffusion because most materials that produce radon have low permeability. In the soil, the effective diffusion coefficient depends on the soil porosity and water content, and that permeability depends on the soil type, porosity and water content (Neilsen et al., 1994).

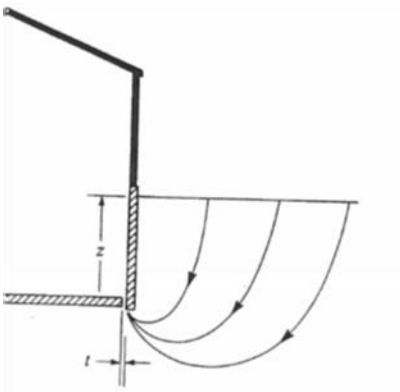
Mustonen has examined the radium concentrations of typical stone-based building materials and their radon generation values (Mustonen, 1984). According to Mustonen, in a typical house built on the ground, the radon generation of a diffusion source is about 2 Bq m^{-3} h^{-1} based on calculations using the defined generation values of the building materials touching the ground. In a comparison of the radon concentrations in winter and summer conditions in a large national sample survey, it was estimated that the average diffusive radon source strength in a one-family house with a concrete slab foundation was approximately 6 Bq m^{-3} h^{-1} with an average indoor and outdoor temperature difference of 17 ^{o}C (Arvela, 1995ab). In houses built from concrete elements, the radon released from the building materials typically results in a radon concentration of 20-70 Bq m^{-3}. In detached houses, where only the slab foundation is concrete, the floor slab effect on the radon concentration is below 20 Bq m^{-3} (Arvela et al., 2010).

2.1.2 Radon transport

The most important radon transfer mechanism into room air is the convective flow of soil air containing radon, which occurs through those parts of the building that are in contact with the ground. Radon convective flow depends on the pressure difference, and it increases with the depressurisation of the indoors relative to the soil if the sub-floor has leaks into the living space. Physical models have demonstrated that a pressure difference above the sub-floor slab is affected by the pressure difference between the building's indoor and outdoor air, so that as the depressurisation of the building increases the pressure difference above the slab also increases (Mowris and Fisk, 1988).

Classically, the convective flows of soil air that contain radon can be examined in the same way as heat transfer by convection, eq. 1-6. The flow resistance of the soil can be shown in a simplified form by an equation derived from the heat transfer equation (Mowris and Fisk, 1988):

$$R_{soil} = 2\mu \frac{\cosh^{-1}\left[2\frac{z}{t}\right]}{2\pi k_s L} \ , \qquad \textbf{(2)}$$



where

R_{soil} = flow resistance of the soil (Pa s m^{-3})

μ = soil gas viscosity (Pa s)

k_s = soil permeability (m^2)

L = length of the slab wall gap or crack (m)

z = distance from the soil surface to the upper surface of the slab (m)

t = gap width (m)

Figure 1. Transfer of soil air

According to the soil flow resistance equation, the resistance is lower and accordingly the soil gas flow is greater at the edges of the slab, which is typically where any gaps are to be found.

When the flow resistance of the slab against that of the soil (R_b) is considered, the soil gas flow is given by the equation:

$$Q_{soil} = \frac{\Delta P_{tot}}{R_b + R_{soil}} \ , \qquad \textbf{(3)}$$

where Q_{soil} = flow speed of soil gas (m^3 s^{-1})

R_b = flow resistance of the slab gaps (Pa s m^{-3})

ΔP_{tot} = pressure difference between indoor and outdoor air (Pa)

The soil gas flow resistance at the edges and cracks of the slab can be shown by the equation (Mowris and Fisk, 1988):

$$R_b = \frac{C_f\ \mu\ L_s}{12\ L\ t^3}\ , \qquad \textbf{(4)}$$

where	L_s	=	slab thickness (m)
	t	=	gap width (m)
	C_f	=	3, if 0.3 mm ≤ t_{crack} ≤ 0.7 mm
			1.6, of 0.3 mm ≤ $t_{wall\ gap}$ ≤ 0.7 mm
			1 otherwise

When R_b (4) and R_{soil} (2) are combined, the flow of the soil gas in soil can be calculated from the equation (Mowris and Fisk, 1988):

$$Q_{soil} = \frac{L\ \Delta P_{tot}}{\mu}\left[\frac{C_f L_s}{12\ t^3} + \frac{1}{\pi k_s}\cosh^{-1}\left[\frac{2z}{t}\right]\right]^{-1}\ , \qquad \textbf{(5)}$$

The flow of soil gas Q_{soil} increases in direct proportion to the pressure difference, ΔP_{tot}, the soil permeability, k_s, and the total length of any gaps or cracks in the slab wall, L. There is a corresponding decrease in the flow of soil gas as the thickness of the slab L_s increases. The effect of the ratio $2z/t$ effect on the flow rate is related to the hyperbolic cosine function (1...∞) and the model's flow rate of soil gas increases as the ratio decreases. As the width of the gap *t* increases, the flow rate increases to the third power of t. In a sub-floor structure that is not equipped to prevent radon or gaseous substances in the soil, the most important factor that affects the flow through gaps, Q_{soil} is, however, the soil permeability. The flow resistance of the slab gaps R_b (generally t ≥ 0.5mm) does not significantly restrict the flow of soil air through the gaps.

Soil gas containing radon typically flows into houses with a ground-supported concrete slab that is not airtight at 0.2-2 $m^3\ h^{-1}$ depending on the permeability of the soil (Arvela, 1995ab).

Equation (4) can be applied, for example, in evaluating the rate of convective radon entry *S*. When the radon concentration C_s of the soil gas is known, the source strength is then resolved by the equation:

$$S_f = \frac{Q_{soil}}{V} C_s \ , \qquad \textbf{(6)}$$

where
S_f = rate of radon entry, convective radon source (Bq m^{-3} s^{-1})
V = volume of the space being examined (m^3)
C_s = soil gas radon concentration (Bq m^{-3})
Q_{soil} = flow rate of soil gas (m^3 s^{-1}) **(5)**

Radon transport mechanisms include diffusion, convection, decay and generation. Diffusion is controlled by the concentration gradient between the surface and underground, which leads to diffusive radon flow to the surface. The convection mechanism is mainly induced by the air pressure difference in the subsurface. Considering radon transport mechanisms, the rate of change of radon concentration in soil pore air can thus be derived by the transport equation as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial}\left(D\frac{\partial C}{\partial x}\right) - Q_{soil}\left(\frac{\partial C}{\partial x}\right) - \lambda_{Rn} C + G \ , \qquad \textbf{(7)}$$

where
D = radon diffusion coefficient (m^2 s^{-1})
x = distance from the surface exposed to radon (m)
C = radon concentration in soil pore air (Bq m^{-3})
Q_{soil} = flow rate of soil gas (m^3 s^{-1})
λ_{Rn} = radon radioactive decay constant (s^{-1})
G = radon generation rate (Bq m^{-3} s^{-1})
t = time (s)

However, the equations 1 to 7 do not include all of the factors related to radon flow and concentration. The equations are not adequate for describing the time-varying effect of pressure and temperature difference on the radon entry rate from soil into a building. Modern approaches are based on a differential equation describing non-stationary diffusive and convective transport of radon in a porous medium. Soil gas flow will be balanced by outdoor air coming through the soil. If the impact time of the air flowing in the soil is short, the radon concentration of soil gas will not reach the concentration in the soil. The wind can also have a diluting effect in the soil below a building and thus reduce the radon concentration of the soil gas passing through the slab.

If the building is located on an esker, the soil gas flow and radon concentration are affected by several factors in addition to the wind, such as the building's location on the esker, the season and the soil's convective flows. Wind in esker areas can generate soil gas flows inside the eskers, inhibiting or promoting convective flows in the soil and affecting the ventilation of the soil in the immediate vicinity of the building.

Several attempts to model and predict the radon concentration in indoor air may be found in the current literature, (Kohl et., 1994; Andersen C, 2001; Font, 1997, Font et al., 2001; Revzan et al., 1993; Revzan et al., 1991; Nazaroff et al., 1988; Mowris and Fisk, 1988; Arvela et al., 1988; Gatalano et al., 2015; Jelle B, 2011; Jelle B, 2012; Albarracín et al., 2002; Savović et al., 2011; Svoboda, 2000; Catalano et al., 2015). Models have been developed to calculate the radon concentration in indoor air, or there are methods which enable the estimation of radon concentration in a building. Such models and methods take into account various important parameters, e.g. the radon concentration in the ground, the radon diffusion resistance of radon barriers, the air permeability of the ground, the air pressure difference between indoors and outdoors at ground level, the ground ventilation in the vicinity of the building and the ventilation rate of the building. The latest models are based on a differential equation describing non-stationary radon transport in a porous medium. These models have been developed to simulate vertical profiles of radon concentration in soil and the entry of soil gas and radon into houses. They take into account the response to changes in atmospheric pressure, or indoor-outdoor pressure differences, the total ventilation of the building and they calculate the radon exhalation rate from the building materials. Moisture is included in such models and the distribution of radon between the air, the detailed geometry of the building's foundations, and the size and water content of the soil grain is taken into account. Many parameters like diffusivity and permeability may be anisotropic. Radon transport models can deal with calculations where the soil gas, the radon generation and weather parameters are time-dependent.

2.2 Combining the pressure differences

The pressure difference between the building's indoor and outdoor air, ΔP_{tot}, is made up of the following factors:

1. The temperature difference between the indoor and outdoor air, which causes a pressure difference, ΔP_{stack}
2. The wind, which causes a pressure difference, ΔP_w
3. The ventilation system flow imbalance and other devices that cause a pressure difference, ΔP_{umv}

The temperature difference for the calculation of radon generation, and the imbalance between the wind and the ventilation system flow can be combined to give the building's pressure difference at the height of the sub-floor slab (Mowris and Fisk, 1988):

$$\Delta \mathrm{P_{tot}} = \Delta \mathrm{P_{stack}} + \Delta \mathrm{P_w} + \Delta \mathrm{P_{umv}} \quad , \qquad \textbf{(8)}$$

The pressure difference from outside the building through the soil can be made up of the wind, the soil's convective flow and changes in atmospheric pressure.

The depressurisation of the building is affected not just by the ventilation, but also factors like an oven extractor fan, a centralised vacuum cleaning system, fireplaces and flues (Keskikuru, 1994a). Their use and impact vary, but usually the timing of their use is not very significant.

2.2.1 Pressure difference due to the stack effect ΔP_{stack}

The temperature difference between the indoor and outdoor air causes a pressure difference in the building which changes vertically. If the outdoor temperature is colder than the indoor temperature, the lower part of the building is depressurised and there is an overpressure in the upper part. The location and quantity of leakages, however, significantly affect the vertical position of the neutral axis. Nevertheless, if the building is completely airtight or the leaks are evenly distributed the neutral axis is located mid-way between the walls.

Depressurisation in the lower part of the building causes air infiltration from the soil to enter the living spaces, while overpressure at the top of the building causes air to leak out through the wall and ceiling structures. The pressure difference is caused by differences in the density of the air at different temperatures. The pressure difference can be calculated from an equation that applies in unventilated conditions (Sherman, 1980):

$$\Delta P_{stack} = -\rho_{out}\, g\, \frac{\Delta T}{T_{in}+273}\,(z - z_n) \quad , \tag{9}$$

where

	ΔP_{stack}	=	pressure difference caused by temperature difference at distance z from the neutral axis of the building's wall z_n (Pa)
	z_n	=	neutral level of pressure difference (where ΔP_s = 0) (m)
	ΔT	=	temperature difference between indoor and outdoor air (°C)
	g	=	standard acceleration due to earth's gravity (m s^{-2})
	ρ_{out}	=	outdoor air density (kg m^{-3})
	T_{in}	=	indoor temperature (°C)

2.2.2 Wind induced pressure difference ΔP_w

When the air mass of wind meets a building, it causes a pressure difference over the building's envelope, which increases the volume of leakage air. The pressure field that forms over the external surfaces of the building changes constantly because of wind turbulence. The magnitude of the pressure field depends on the wind direction and speed, the building geometry, the surfaces and the immediate environment. The building envelope on the windward side is subject to overpressure and internal areas on the leeward side will be subject to depressurisation. Since the wind speed increases the further it is from the ground, the effect of the wind is greater on the upper parts of a building.

The leakage flow resulting from the pressure differences in the building or in parts of it can be described using a traditional leakage equation:

$$Q = k\,\Delta P^{n} \quad , \tag{10}$$

where Q = infiltration air flow ($m^3\,s^{-1}$)

ΔP = pressure difference across the building envelope (Pa)

k = flow factor ($m^3\,s^{-1}\,Pa^{-n}$)

n = flow exponent

The flow exponent *n* is determined by pressure testing. In an area of laminar flow n=1 and in a very turbulent flow area n=0.5 (Sherman et al., 1984). The flow factor is not a constant, but instead it changes in different areas at different times and over a wide pressure range (Siitonen V, 1978). Laminar and turbulent flows occur at the same time, because the area of the leakage flows varies constantly. For the same reason, the flow rate does not change at the same time the pressure difference changes. This reduces the usefulness of the equation for areas of small pressure difference, which is typical in buildings fitted with supply and exhaust ventilation. However, in most houses the flow exponent is $0.55 \leq n \leq 0.75$. In a study that investigated the airtightness of 196 houses, the result was a mean for the flow exponent n of 0.66 (Sherman et al., 1984). Jokisalo et al. obtained a mean of 0.73 for the exponent in the Finnish building in their study (Jokisalo et al., 2008).

2.2.3 Pressure difference caused by mechanical ventilation ΔP_{umv}

According to the Finnish building code for indoor air and the ventilation of buildings, the building is generally designed to be slightly depressurised with respect to the outdoor air in order to avoid dampness-related damage to structures, and health hazards caused by microbes. However, the depressurisation cannot usually be greater than 30 Pa (D2). The Finnish Ministry of Social Affairs and Health has given guidelines for differences in indoor-outdoor pressure in a building as well as those that depend on different ventilation systems (Table 1) (Guide for Occupational Health, 2009).

Table 1. Guidelines for differences in indoor-outdoor pressure in different ventilation systems (Guide for Occupational Health, 2009).

Ventilation system	Pressure difference
Natural	0…-5 Pa indoor-outdoor 0 Pa indoor-staircase
Exhaust	-5…-20 Pa indoor-outdoor 0…-5 Pa indoor-staircase
Supply and exhaust	0…-2 Pa indoor-outdoor 0 Pa indoor-staircase

The effect of mechanical exhaust ventilation and natural ventilation on pressure differences has been studied in Finland (Leivo et al., 2015). The research looked at differential pressure measurements between indoors and outdoors, and between indoor air and air in the stairwell in 156 flats in 26 blocks. In all of the sites equipped with mechanical ventilation of exhaust air (n=137) the difference between indoor and outdoor air varied between +10 Pa to -95 Pa (average-7.8 Pa), and between indoor air and air in the stairwell from -3.5 Pa to -76 Pa (average -18.6 Pa). In flats with natural ventilation (n=10) the difference between indoor and outdoor air varied from -1 Pa to -15 Pa (average-7.0 Pa) and between indoor air and air in the stairwell from -0.4 Pa to -14.9 Pa (average -4.5 Pa). The average pressure difference between the indoor air and outdoor air for mechanical exhaust ventilation corresponded to the building code recommendation, and the pressure difference between indoor air and the air in the stairwell exceeded the recommendation. In flats with natural exhaust ventilation, the average pressure differences exceeded the recommendations.

In a second study carried out in Finland (Seppänen K, 2010) pressures differences between the building's indoor air and outdoor air were measured at 176 different sites. According to the results of these measurements, there was, on average, depressurisation of -8 Pa with respect to the outdoor air. The research found that more than 30% of the measurement results were more than 10 Pa. The research sample was not homogeneous and varied according to type of construction, ventilation method and year of construction. There were 24 detached houses in the study, 10 of which had mechanical supply and exhaust ventilation. About half of the detached houses which had supply and exhaust ventilation had a slight overpressure.

Depressurisation in buildings at the Tuusula Housing Fair site were studied in 2002 by Helsinki University of Technology and the Radiation and Nuclear Safety Authority

(Airaksinen et al., 2002). The research gives a representative image of the Finnish building stock at that time. Depressurisation in houses with exhaust ventilation was approximately twice (7 to 10 Pa) that of houses with a supply and exhaust system (2 to 5 Pa).

A mechanical exhaust ventilation system creates higher depressurisation than a mechanical supply and exhaust ventilation system. The pressure difference with a mechanical supply and exhaust ventilation system is affected by the supply and exhaust flow difference and the airtightness of the building. Other factors that affect the difference in indoor and outdoor air pressure are the location of the supply and exhaust vents in the rooms, the adequacy of the transferred air routes between rooms, the regulation of air volume and the change in these volumes at different ventilation levels. The pressure difference caused by the system can be reduced by balancing air flows. **Publications IV and V utilize these approaches.**

The ventilation is adjusted so that there is just enough depressurisation in the building to prevent condensation damage to the structures. In a mechanical supply and exhaust ventilation system, this is achieved by setting total supply air flow in single-storey detached houses at 15% (or 20%) lower than total exhaust air flow, while the corresponding value in two-storey houses is 25%. The resulting pressure difference can be checked roughly using the leakage equation (10). According to the design instructions, using ventilation to create a pressure difference over the outer envelope involves selecting 2 Pa for a single-storey building and 4 Pa for a two-storey building, so that there is no overpressure in the upper storey of the building. This pressure difference is intended to maintain depressurisation in the upper part of the building in winter, too. The pressure differences are achieved by calculation for an airtight, single-storey house (airtightness Q_{50} is 1) with a 15% difference in air flows, and in two-storey houses with a 25% difference in air flows. The building envelope airtightness requirements have now increased and in today's buildings, improved airtightness and differences in the ventilation supply and exhaust air flows may lead to significant pressure differences (Kalamees et al., 2007 and Arvela et al., 2014). Depending on the location of leaks in the building envelope, there may be leakage airflow from the soil through gaps in the ground floor or there may be a risk of airflow into the upper floor from damaged structures.

2.3 Changes in the soil gas flow and radon concentration under the slab of the building and in the surrounding soil

Wind pressure causes a pressure field at ground level near a building. This field changes continuously as the wind direction and speed vary. It can be examined using scale model tests in a wind tunnel. The formation of the field and its effect on the building's radon source strength is difficult to handle theoretically. When assessing the effect of wind on radon, the individual characteristics of each situation should always be considered.

Pressure propagation time in the soil varies widely, depending on the soil type and distance. Propagation time is short in soil types with high permeability, and the wind can cause a significant pressure difference across the slab as well as increasing the flow speed of soil gas through the slab (Nazaroff et al., 1988). In contrast, Rowe et al. reported that the variations in most indoor radon concentrations are explained by temperature, with smaller effects relating to wind speed, rainfall and barometric pressure.

In research by the Radiation and Nuclear Safety Authority, it was shown that the flows of soil gas in esker areas significantly affected the radon levels in the soil that was in contact with the building and the indoor air. Temperature differences between the outdoor air and soil were found to be the most important causal factor with regard to the flows of soil gas. In the winter, soil and room air radon levels were higher in the upper part of the esker, and in summer as the convective flows turned to the lower part of the esker, higher levels were measured than at the top of the esker. In winter, the wind striking the esker increases the radon levels caused by temperature difference in the upper part of the esker, but in the warmer periods of the summer, even strong winds were not able to reverse the soil gas flow and radon concentration levels. Similarly, the wind striking the esker in the summer reduced the high radon level caused by soil air flow at the bottom of the esker (Arvela H et al., 1994). **Publications III examines the impact of the wind direction on the radon levels at the research sites in the esker area.**

As stated above, wind pressure causes a pressure field around a building. The effect of the pressure field on the soil and the radon levels in room air can be examined using calculation models and experimental measurements. The Riley calculation model combines a calculation model for room air radon levels with a calculation model for the ground level pressure field. A 3D model is used to calculate the pressure field on the soil caused by the wind, the soil gas flows caused by the pressure field and the soil radon concentration levels. After this, the radon concentration in the room air can be determined from the soil radon concentration, the convective flow and the air change in the building (Riley et al., 1996). According to Riley's calculations, the wind reduces the radon concentration in room air because the pressure field near the building caused by the wind dilutes the radon concentration in the soil air and at the same time increases the rate of air change in the building. The dilution effect of the wind is greatest at the edges of the building on the windward side. Most of the areas of leaks from a building are located at the edges. The wind causes air to flow from the windward side of the building to the ground and under the building, exiting from the soil on the leeward side. The flow of soil air caused by the pressure field and the wind increases with increasing permeability of the soil. **Publications I to III and V examine the importance of the wind as an explanatory factor for radon levels.**

The effects of changes in barometric pressure and the suddenness of the change on the leakage of soil air and the generation of radon through structures touching the ground have seldom been studied, and what studies there are have yielded conflicting results. **Publication II reviews the effect of changes in barometric pressure on indoor air radon levels.** Marley found that indoor radon was primarily dependent on the barometric pressure and wind variation (Marley, 2001). In contrast, Kitto observed that diurnal indoor radon levels were heavily influenced by indoor-outdoor temperature difference, with little correlation to barometric pressure and wind speed (Kitto, 2005). Dolejs also found changes in barometric pressure did not affect the rate of radon entry (Dolejs, 2003). In Müllerová's study, the radon activity in the soil has been monitored continuously since 1994. The results of this long-term continual monitoring of radon activity concentration in the soil air at a depth of 0.8 m show great variability, with daily and seasonal variations. Long-term measurements at a depth of 0.8 m and short-term measurements at a depth of 0.4 m showed a high variability in radon activity concentrations in the soil. The analysis of the data confirmed that regular daily changes in radon activity concentration in the soil air depended on the daily changes in atmospheric pressure (Müllerová et al., 2014).

It has been suggested that barometric pressure changes increase radon generation through the slab in cases where the permeability of the soil is high, and the soil surface is frozen (Nazaroff et al., 1988). A similar situation occurs, if the surface of high permeability subsoil is filled with a compact soil type or the surface soil is wet. In their research, Nazaroff et al. did not observe any correlation between changes in barometric pressure and soil gas containing radon (Nazaroff et al., 1985). However, in the same study, heightened radon levels were observed after heavy rain. Some studies have reported that rainfall or increased snowfall could cause unexpectedly high indoor radon concentrations (Mose et al., 1991; Steck, 2009; Francesco et al., 2010; Müllerová et al.,2014). On the other hand, in their research Hintenlang and Al-Ahmady observed that with low permeability soil types, changes in barometric pressure do cause a significant proportion of radon generation through the slab. The phenomenon was observed in a situation where the building's overpressure or depressurisation and air change were low, and there was a regular fluctuation in air pressure every twelve hours (Hintenlang and Al-Ahmady, 1992). In a study carried out in Florida, fluctuations in air pressure were caused by the Coriolis force and the phenomenon also occurs in the southern hemisphere.

A physical model has also been developed for soil gas leakage resulting from fluctuations in air pressure. Using a theoretical model and experimental measurements, Robinson showed that fluctuations in air pressure can cause soil gas flows through the slab into living areas regardless of any contribution from indoor and outdoor air pressure differences (Robinson et al., 1997). According to their study, the soil gas flow through the slab depends on the time response of the pressure change in the soil and the frequency of the change in air pressure. Using spectral analysis and measurements in a test building, it was found that a relatively low frequency of air pressure change ($\leq 100\ d^{-1}$) produced most of the soil gas flow. Barometric pressure variation of more than 60% is located in the frequency range $\leq 100\ d^{-1}$.

If it rains, the permeability at the soil's surface falls compared to the dry soil beneath the slab. This could be a reason for the short-term increase in radon generation, independent of barometric pressure changes (Nazaroff et al., 1988). The effect of soil moisture on indoor air radon levels has also been little studied and the different research results are conflicting. For the soil type at the measurement site, it was possible to observe that precipitation has a significant influence on the concentration of radon activity. The influence of precipitation is strongest in the lower layers of the soil (below 0.4 m). It was also found that the time lag between precipitation and increased radon activity concentrations was dependent on the depth at which the radon was measured. Arvela et al, used multi-disciplinary analysis to study the seasonal effect of soil moisture on the indoor air radon concentration (Arvela et al., 2015). The study consisted of soil gas moisture measurements and the application of the measurement results to determine the radon concentration on the basis of previous theoretical research data. In addition, they compared their results with the results of radon measurements for 386 houses using a simplified calculation model for radon concentration. (Arvela et al., 2015). The calculation model took meteorological factors into consideration and, in addition, soil moisture and its impact on radon generation. According to these results, soil moisture has a significant impact on the seasonal variations of radon concentration in soil.

The proportion of soil radon gas between the water and air fractions of the soil pores is the main factor increasing soil air radon concentration. Higher soil moisture in autumn and spring increases soil gas radon concentrations by 10 -20 %. In winter, the soil gas radon concentration is at its minimum. The soil temperature in summer increased the calculated soil gas concentration by 14 % compared with the winter values. The measured radon concentrations in autumn and spring were higher than expected and this can also be explained by the seasonal variations in soil moisture. (Arvela et al., 2015)

It is virtually impossible to generalise about the effects that wind, changes in barometric pressure and changes in the moisture content of various soil layers can have on the soil gas flow under and in the vicinity of the building. Each situation has to be taken on its own merits. Soil gas flow and soil gas concentration are influenced by many factors, such as the type and depth of the foundation, the airtightness of the building substructure, the vertical profile of soil permeability, the location of the radon source, groundwater level, etc.

2.4 Indoor radon mitigation by ventilation

2.4.1 Estimating the air change rate

The ventilation of a space is a combination of natural uncontrolled air leakage and mechanical ventilation. Natural ventilation is caused by pressure differences in the building envelope resulting from temperature differences and wind effects, and these cause continuous change in air leakage. Air leakage increases the imbalance of mechanical ventilation air flows.

The total ventilation rate for a space can be estimated using the simplified quadratic equation (Modera and Peterson F., 1985):

$$\lambda_v = \frac{\sqrt{Q_s^2 + Q_w^2 + Q_{umv}^2} + Q_{bmv}}{V} \quad , \tag{11}$$

where Q_s = infiltration air flow due to the stack effect ($m^3\ s^{-1}$)
Q_w = infiltration air flow due to the wind effect ($m^3\ s^{-1}$)
Q_{umv} = infiltration air flow due to unbalanced ventilation ($m^3\ s^{-1}$)
Q_{bmv} = mechanical ventilation ($m^3\ s^{-1}$)

This equation overestimates the effect of temperature difference and wind on the amount of leakage air, particular in the case where the effects of temperature difference and wind are equal. (Walker and Wilson, 1993).

In buildings, the practical applicability of ventilation rate calculations is limited. Tracer-gas techniques are useful and have become widely used to measure the mechanical and natural ventilation rates in buildings. There are three basic tracer gas techniques for measuring ventilation rates: decay, constant concentration, and constant injection (Stymne et al., 2002). In **Publication IV**, total ventilation rates and transfer air flows in two detached houses were studied using an integrated tracer gas method with constant injection of perfluorocarbon, PFT.

2.4.2 The expression for indoor radon

Using the mass balance equation, the speed of change of the indoor radon concentration and its dependence on ventilation λ_v, radon decay λ_{Rn}, radon generation S_d and S_f, indoor radon concentration Rn_i and outdoor radon concentration Rn_o can be shown with the following equation (Mowris, 1986):

$$\frac{dRn_i(t)}{dt} = S_d(t) + S_f(t) + [\lambda_v(t) - \lambda_F]Rn_0(t) - Rn_i(t)[\lambda_v + \lambda_{Rn}] \text{ ,} \quad \textbf{(12)}$$

where
λ_F = leakage air change through the slab = $\frac{Q_{soil}}{V}$ (s^{-1})
S_f = rate of radon entry, convective radon source (Bq m^{-3} s^{-1})
S_d = rate of radon entry, diffusive radon source (Bq m^{-3} s^{-1}
λ_{Rn} = radon radioactive decay constant = 2.1×10^{-6} (s^{-1})
λ_v = total air change (s^{-1})
Rn_o = outdoor radon concentration (Bq m^{-3})
Rn_i = indoor radon concentration (Bq m^{-3})
Q_{soil} = soil gas flow rate (m^3 s^{-1})
V = house volume (m^3)

Arvela (Arvela et al., 1988; Arvela et al., 1989; Arvela, 1995a) developed a physical computational model applied to the above-mentioned theory that can be used to examine seasonal fluctuations in radon concentrations in houses built on a slab resting on the soil. The model can be used to evaluate the correction factor for converting an integrated radon measurement result of less than one year to an annual average. Using the model's calculation of the relationship between the forecast and measured winter and summer concentrations, it is estimated that the average diffusive radon source strength for a detached house with a slab foundation is approximately 6 Bq m^{-3} h^{-1}. Similarly, the convective source strength averages 50 Bq m^{-3} h^{-1} with an average annual indoor and outdoor temperature difference of 17 ^oC (Arvela, 1995ab). In a typical single-storey detached house, the concentration of radon in the room air from a diffusive source resulting from the increase in temperature difference decreases with increasing natural ventilation. On the other hand, as the temperature difference increases, the strength of the convective source will also increase because of the increased pressure difference.

In this case, the increased impact of the indoor radon concentration from a convective source is typically greater than the simultaneous increased dilution from natural ventilation. In areas of small temperature differences, the ventilation caused by wind effectively reduces the radon concentration resulting from a diffusive source. The model's results provide a good explanation of the observed seasonal fluctuation in the radon concentrations measured.

2.4.3 Ventilation system for indoor radon mitigation

2.4.3.1 Natural ventilation

Natural ventilation is based on the exchange of leakage air resulting from the temperature difference between outdoor and indoor air and from the pressure difference caused by the wind. Because of the variation in weather conditions, the ventilation air flows fluctuate, and the ventilation system's airflows are difficult to regulate. Natural ventilation is poorly suited to today's airtight building stock. With regard to combating radon, the adequate air change requirement is not met in the summer as the temperature differences are small and the wind speed is generally low during the night due to the effects of the heat from the sun. When the sun goes down, the wind usually weakens and wind turbulence drops (RT 05-10390). In winter, radon convective flows increase as depressurisation of the interior and leaks from the sub-floor increase.

2.4.3.2 Mechanical exhaust ventilation

With mechanical ventilation, dirty air from the kitchen, bathroom, toilet and similar spaces is removed from the premises through exhaust ducts. From the living areas, the air passes into areas fitted with exhaust vents through gaps under the doors. Outdoor air is taken via fresh-air vents and, depending on the airtightness of the building, much of it comes through uncontrollable leakage points in the building envelope. Before 1988, fresh-air vents and exhaust vents in bedrooms were quite uncommon. However, an airtight house needs fresh-air vents. Mechanical exhaust ventilation only deals with part of the requirements set for combating radon. The house must be so airtight so that, in accordance with the building codes, there is an adequate controlled supply air flow coming into the desired areas through fresh-air vents (Heikkinen, 1989). On the other hand, bringing in cold air through ventilation valves into living areas during the coldest season without creating cold drafts is difficult. This leads to reduced ventilation power during the coldest season and at night, when the radon concentration is higher. In an airtight building an exhaust system using ventilation technology causes high depressurisation in the house. Therefore, such systems are not recommended for use, because the depressurisation increases the transfer of soil gas containing radon into the living spaces. Increasing the exhaust ventilation without taking any further measures does not necessarily reduce the radon concentration, and may even increase it.

2.4.3.3 Mechanical supply and exhaust ventilation

When it is correctly designed and installed, mechanical supply and exhaust ventilation can satisfy the most important criteria for radon management in indoor air. **Publications IV and V utilize this approach**. In line with the design instructions (LVI -30-10084 and 10085, 1987) and established practice, heated and filtered supply air is brought into the house using its own fan. This air is then divided using separate ducts and taken into the living areas through supply air vents. Exhaust vents are installed in washing areas, WCs and laundry rooms and channelled to the exhaust air fan. Air transfer routes between living areas and wet rooms use gaps in doors or sound-proofed wall vents. When dimensioning air transfer routes (flow resistance) the pressure difference between different areas and between indoor and outdoor air is of key significance. Regulation of the system is easy, and if it is well-implemented the noise caused by ventilation does not prevent the ventilation being used at night, which is important for efficient radon management. In addition, its use is not limited by drafts during the coldest season. A ventilation system that is implemented in accordance with the design instructions results in significantly lower depressurisation than with mechanical exhaust ventilation.

According to the National Building Code of Building Regulations and Instructions, a building is generally designed to be slightly depressurised with respect to the outdoor air, and wet/humid areas are depressurised with respect to other spaces in the building. The ventilation is adjusted so that there is a slight depressurisation in the buildings in order to avoid condensation damage in the structures. Any additional radon flows caused by the depressurisation can be reduced by balancing the supply and exhaust ventilation air flows.

2.4.4 The effect of mechanical ventilation on radon concentration

Indoor radon concentration can be decreased by ventilation. The percentage decrease in radon concentration with different methods varies according to the method and the particular case. Measures to improve ventilation include the layout of the ventilation system, and regulating the ventilation and using the system efficiently. Using a supply and exhaust ventilation system in areas where the radon concentration needs to be mitigated has achieved greater reductions in concentrations than just using mechanical exhaust ventilation. This prevents the depressurisation caused by mechanised removal of air in an airtight house. However, the pressure difference formed in a supply and exhaust ventilation system is more complicated than in a mechanical exhaust system. **Publications IV and V utilize this approach.**

Radon source strength was found to increase when the convective flow from the soil increased as a result of increased pressure difference. The highest concentrations of radon and depressurisation were found in houses that only had mechanical exhaust ventilation (Kokotti et al., 1989). When the depressurisation was low, the source strength remained low and almost constant. Holub (1985) has also shown that a small pressure difference (0.8 Pa) significantly increases the indoor radon concentration.

A study in California (Turk et al., 1991) examined experimentally the effect of pressurisation on radon source strength in five buildings. Pressurisation was achieved by blowing air from the top storey to the ground floor. For each site, the ground floor was over-pressurised in steps (1...6 Pa) and radon concentrations were measured for each level of pressure difference. The radon concentrations on the upper storey, measured before the study, ranged from the highest concentration at approximately 4000 Bq m^{-3} and the lowest at approximately 550 Bq m^{-3}. The top storey concentrations decreased to less than 148 Bq m^{-3} (EPA indicator value) at an overpressure of 1-3 Pa. At two sites, the effect of a very slight overpressure ($\leq$1 Pa) on the concentration was studied. The result was a reduction in the initial concentration of over 50%. The reduction in radon concentration was greater, the higher the overpressure used. The study did not identify the separate effects of increased ventilation and the pressure difference on the reduction of the radon concentration. In addition, it was observed that the pressure increase affected the reduction in radon concentration differently at each site. One disadvantage of this method mentioned in the study is the risk of the structures getting wet, and the problems this can cause.

Research at Tampere University of Technology examined the effect of increased ventilation in reducing indoor radon concentrations in nine detached houses. By repairing and regulating the mechanical ventilation control and installing a supply and exhaust ventilation system, a reduction in radon concentrations of 35-80% was achieved. The best results were achieved using supply and exhaust ventilation, with the supply air regulated at a maximum of 10% less than the exhaust air to minimize depressurisation (Keskinen et al., 1989). In research by the Radiation and Nuclear Safety Authority, the use of mechanised supply and exhaust ventilation reduced the radon concentration by between 20% and 80% (Hoving et al., 1993). According to research by the Radiation and Nuclear Safety Authority and Helsinki University of Technology, air change was, on average, higher in houses with mechanical ventilation than in similarly constructed houses with natural ventilation. However, radon concentration is on average slightly higher in houses with mechanical ventilation (Ruotsalainen et al., 1997, Arvela, 1995b). In terms of results it is important that the ventilation is technically correct and efficiently implemented; the radon concentration can sometimes be brought down to the recommended level by the continuous use of efficient ventilation.

According to the results of the Radiation and Nuclear Safety Authority's national sample study, indoor radon concentrations have decreased in detached houses built during the period 2000-2005 by around 15% compared to those built from 1980-1999, when radon concentrations were at their highest. Detached houses built between 2006-2008 have more than 40%, lower radon concentrations than houses built during the 1980s and 1990s (Arvela et al., 2010). Switching to a supply and exhaust ventilation system is a potential factor affecting changes in radon concentrations in detached houses of different ages. Based on a sample survey of Finnish detached houses' ventilation systems, since the 1980s detached houses have switched to using supply and exhaust ventilation. During the first few years of the 21st century, the penetration of supply and exhaust ventilation was already about 75% and, according to the results of the survey, it had reached 93% for the years 2006-2008. In terraced houses the corresponding increase in the use of supply and exhaust ventilation was from 45% to 93% (Mäkeläinen et al., 2009). Given the significant difference between the level of depressurisation caused by exhaust ventilation and supply and exhaust ventilation systems, it is likely that the switch to supply and exhaust systems in semi-detached and row houses must have contributed to the reduction in radon concentrations in row houses and in the whole stock of detached houses (Arvela et al., 2010).

Research carried out at the University of Kuopio examined the effect of using supply and exhaust ventilation along with pressure difference regulation on the indoor radon concentration in six houses constructed with ground-supported concrete slab foundations. Five of the houses had previously had supply and exhaust ventilation and one had only had exhaust ventilation. The ventilation system with pressure difference regulation reduced radon concentrations by from 40 to 88%. The highest reduction in radon concentration was measured at the site with the highest concentration. The house had previously had exhaust ventilation, which was used for approximately two hours a day. The radon concentrations at the houses reduced as the depressurisation fell and as the air change was intensified. Temperature difference caused the greatest increase in radon source strength in the leaky houses, where the source strength peaked locally when selecting a slight depressurisation, unlike in the most airtight houses (Kokotti et al. 1994 ab; Kokotti, 1995).

Kokotti et al. investigated the effect of pressure difference on radon source strength in eight houses constructed with ground-supported concrete slab foundations (there were two sites in addition to the previous ones) which were located in areas with three different soil types. Normalized radon entry was estimated using the indoor radon concentration and pressure difference measurement results. Normalized radon entry was also examined using a 3D calculation model developed for a theoretical study (Bonnefous et al., 1992). The calculation model used in the examination "Non-Darcy STAR" is an application of Darcy's law. The normalised radon entry at the sites fluctuated between 2×10^{-6} m^3s^{-1} and 9×10^{-4} m^3s^{-1}. According to the measurements and the calculation model, when the pressure difference gradient fell from zero to -10 Pa, the normalized radon entry increased a thousand-fold. The normalized radon entry increased linearly, but when the negative pressure gradient dropped below 4 Pa, the draining of radon from the soil was significant and normalised radon entry levelled off. Diffusive radon entry was still possible when the pressure difference was zero through gaps in the structures. In the study, it was observed that when there was sufficient overpressure ($>$2 Pa and with a soil permeability of $\geq10^{-11}$ m^2) the amount of radon entry was very low (Kokotti et al., 1996).

It is difficult to achieve sufficiently low radon concentrations by increasing ventilation when radon concentrations indoors are high, and other methods must be used in addition to ventilation. The best results using ventilation were obtained in buildings where ventilation had hitherto been ineffective, or depressurisation had been high before measures were taken to improve the ventilation system. The disadvantage of this kind of radon mitigation is the difficulty of predicting their effectiveness.

The most effective mitigation methods are mechanical sub-slab depressurisation and a radon well. Indoor radon reduction factors have been 70-90 % using this method (Arvela et al., 2008; Arvela et al., 2011; Jiránek, 2014).

2.5 Measurement of pressure difference

Many researchers have confirmed the effect that pressure difference has on soil gas flows. However, it is difficult to determine the precise effect that the wind has when measuring the pressure differences around a building’s envelope because the results of the measurements are strongly dependent on the locations at which they are taken, and the prevailing wind direction. Even pressure differences measured at points close together on the same wall can vary greatly (Luoma and Marjamäki, 1987). The prevailing pressure differences between indoors and outdoors and between indoors and the soil, and the temporal variation and correlations between them have not been widely studied.

In radon studies, pressure difference is measured in different ways. Naturally, pressure difference measurements are more accurate, the more points of measurement there are. For example, in a study by Nazaroff et al, the pressure difference was measured over four walls with all the measurement points being at the same height (0.3 m) from the floor and the soil surface, and the average pressure difference was used in the comparison (Nazaroff et al., 1985). Although the use of the average and the height of the external measuring points were not explained in more detail in the study, theoretically, the average pressure difference measured over four walls should correspond to the model presented by Mowris and Fisk if the pressure difference between the roof and indoors is also taken into account. The effect of the height of the external measuring point on the pressure is affected by the wind. The wind creates a fluctuating pressure field on the building's wall, and the degree of pressure changes according to height. However, the vertical change in air pressure (approximately 100 Pa / 8 m) is not critical if the pressure difference measurements are all taken at the same height.

In their research, Hintenlang and Al-Ahmady measured the pressure difference across each wall of a building’s envelope. They used attenuation solutions at the external measurement points and it was assumed these would attenuate sudden changes in pressure due to the wind (Hintenlang and Al-Ahmady, 1992).

An open attic can also be used as an external pressure difference measurement point. According to a study conducted by the Technical Research Centre of Finland, the pressure difference between the attic and indoor air is virtually independent of the wind speed, and an attic works well in balancing wind pressure (Korkala and Siitonen, 1986; Karvonen and Virtanen, 1988). One of the conditions for an attic to balance pressure is that it is big enough not to cause any significant flow resistance. If the attic is small and there are few airflow gaps, this will increase the effect of the wind on the measured pressure difference. The pressure difference and the pressure difference variations are likely to increase but are still generally lower on the leeward side than on the windward side of the wall. The ends of the eaves must also be as symmetrical as possible, as this can affect their leakage characteristics (Karvonen and Virtanen, 1988).

2.6 Airtightness of residential buildings in Finland

The airtightness tests in our study followed the procedures detailed in (EN 13829, 2000), which cover the thermal performance of buildings and determination of their air permeability. The test involves connecting a fan to a suitable aperture in the building envelope, and then to pressurise the building over a range of pressure differences. During the test, all the openings in the envelope are closed and sealed when needed. The fan speed is increased step by step up to a maximum prescribed value, and then decreased over the same steps. The volume and flow rate of air through the fan is equal to the air leaking through the building envelope, and the pressure difference across the building envelope is recorded at each fan speed. Corrections are made for temperature and barometric pressure in order to calculate the air permeability of the building, and thus a so-called building leakage curve can be calculated as an equation (19).

Technical Research Centre of Finland building and transport carried out 174 airtightness tests on existing houses between 1991 and 1998. The average values of one-family house (n=56) was 5.3 h^{-1} and the average values of detached houses (n=102) 5.6 h^{-1} (Kauppinen, 2001).

In a wide-ranging study carried out in Finland from 2002 to 2009 (Vinha et al., 2015), the airtightness of 170 detached houses and 56 row houses were measured using the fan pressurisation method at 50 Pa. The average age of the measured houses was 2.3 years.

The houses covered different construction types. There were 10 autoclaved aerated concrete block houses, 10 shuttering concrete block houses, 10 concrete element ones, 10 brick masonry ones, 10 lightweight aggregate concrete block houses, 100 timber-framed houses and 20 detached log houses. The mean air change rates of these houses were 1.5 h^{-1}, 1.6 h^{-1}, 2,6 h^{-1}, 2.8 h^{-1}, 3.2 h^{-1}, 3.9 h^{-1} and 6.0 h^{-1}, respectively. The study confirms Kauppinen's observation about the improvements in the airtightness of buildings over the past 30 years. According to Vinha's study, however, good airtightness was achieved in each of the individual houses, regardless of the building type, number of stories, ventilation system or structure.

2.7 Conditions in the crawl space

2.7.1 Hygrothermal condition in the crawl space

The moisture in the crawl space comes mostly from the soil moisture and the moisture content of the ventilation air brought in from outside. **Publication V utilizes this approach.**

The evaporation rate of soil moisture in the crawl space depends on the properties of the gravel infill, the solution used for damp proofing and the air flow rate in the crawl space. Soil moisture flow can be reduced, for example, by placing a damp-proofing layer over the bottom of the crawl space. A gravel layer used as a damp course on the bottom of the crawl space lowers the temperature in the crawl space in the summer and raises it in the winter. (Matilainen and Kurnitski, 2003; Kurnitski and Matilainen, 2000). The temperature decreases during the summer and the resulting increase in the relative humidity of the air in the crawl space results in more condensation on the surfaces there. This can be reduced by reducing the high thermal capacity of the crawl space soil and foundations (Matilainen and Kurnitski, 2003). Thermal insulation of the soil can reduce the relative humidity in the space in conditions where the water content of the outdoor air is high. A lightweight clay aggregate layer (LWA) restricts the evaporation of moisture from the surface of the ground; the thicker the layer, the lower the evaporation. In addition, LWA has higher moisture permeability than expanded polystyrene (EPS) insulation. As a rule, the moisture output from the soil is higher in winter than it is in summer. Increasing the ventilation increases the moisture output from the soil, but it also removes moisture from the crawl space. LWA also works as a capillary break and thermal insulation.

When using a gravel fill as a damp proof course and capillary break, care must be taken to ensure that the gravel is sufficiently coarse, and that the layer is thick enough.

2.7.2 Ventilation and pressure difference in the crawl space

In the Nordic countries, crawl spaces are typically outdoor air-ventilated. In older buildings, ventilation is often natural, but it is often inadequate in buildings with low crawl spaces. Mechanical ventilation is quite common in newer buildings.

According to research, infiltration air enters a depressurised building from the crawl space through leakage routes in the sub-floor structure to the interior. The building depressurisation caused by the ventilation, the stack effect and the wind all affect the pressure difference between the crawl space and the indoors and, through this, air leaks. In the Nordic climate, buildings maintain a slight depressurisation in relation to the outdoor air. Because of this, the sub-floor must be sufficiently airtight to prevent air flowing from the crawl space into the living space via gaps and leaks in the sub-floor. If the air change is high in winter, the crawl space may freeze. In the summer, a high air exchange increases the relative humidity in the crawl space and thus increases the risk of condensation in situations where the water content of the outdoor air is high. A building's mechanical exhaust ventilation causes higher depressurisation indoors than mechanical supply and exhaust ventilation. The magnitude of the pressure difference is also affected by the airtightness of the building and its height. In buildings with natural ventilation, the pressure difference is influenced by the stack effect, in which case the indoor areas are depressurised with respect to the crawl space most of the time. A naturally ventilated crawl space must be sufficiently high, and must have enough well-placed openings to the outdoor air for the required ventilation and flushing effect to be achieved. However, according to Laukkarinen and Vinha's measurements from five cold crawl spaces, excess vapour in the crawl spaces did not correlate directly with wind speed (Laukkarinen and Vinha, 2017). In a crawl space equipped with mechanical exhaust ventilation, ventilation and flushing can be enhanced with exhaust air ducts in the crawl space. Typically, fresh air vents are located in the plinth or fresh air is fed into the space through fresh air pipes. It is not usually possible to regulate air flows with fresh air vents, so the crawl space cannot be depressurised with respect to the outdoor and living spaces. Pressure differences can be best regulated in buildings with mechanical supply and exhaust ventilation. In this case, balanced supply and exhaust ventilation causes the least air leakage from the crawl space into the living space.

Matilainen found that when using a thin, 15-cm LWA layer or a 5-cm EPS insulation plate, the amount of air change in the crawl space must be increased to at least 2 complete exchanges of air an hour. On the other hand, with a 30-cm thick LWA layer or a 10-cm thick EPS insulation layer, 0.5 exchanges an hour is adequate throughout the year, which means that natural ventilation through vents is sufficient (Matilainen and Kurnitski, 2003; Airaksinen, 2003). The recommended insulation solution reduces the high thermal capacity of the crawl space foundation and soil, and thus reduces the increase in relative humidity during the wettest time of the year (the summer). In his research, Kurnitski found that when using gravel fill as a damp-proof course in the winter, the minimum relative humidity was reached with 2-3 air changes, and in the summer the relative humidity decreased by increasing the air change with no upper limit (Kurnitski and Matilainen, 2000). **Publication V utilizes this approach**

2.7.3 Microbiological conditions in the crawl space

According to a wide-ranging study covering several properties, microbe damage in the crawl space is common. Some degree of mould damage was observed in about 70% of properties in the study. In Finland, which has a sub-arctic climate, humid conditions in cold crawl spaces become critical in the summer when the crawl space temperature is significantly colder than outdoors, and the water content of the outdoor air is high. The relative humidity of outdoor air during the Finnish summer is typically 60 to 70 %, and can rise above 80% on particularly humid days. The temperature in the crawl space is considerably lower than that of the outdoor air as the cool ground and massive foundations cool the crawl space. The warm and humid ventilation air from outdoors is cooled in the crawl space, which causes the relative humidity to increase. In studies of crawl spaces, long-term 70-90% relative humidity has been observed (Airaksinen et al., 2003; Kurnitski, 2000; Samuelsson, 1994; Johansson et al. 2013; Iwamae et al., 2003; Laukkarinen and Vinha, 2017). In research carried out at Tampere University of Technology, continuous hourly temperature and relative humidity measurements were taken for a year for five cold crawl spaces. According to this study, different crawl spaces behaved differently. The numbers of hours in a year when the relative humidity was over 80 % or 90 %, varied from 8752 hours to 2760 hours and from 6801 hours to 335 hours (Laukkarinen and Vinha, 2017). Because there is always organic material in a crawl space for mould to feed on, the conditions are favourable for the start of growth (Gradeci et al., 2017; Viitanen et al., 2010). Therefore, weather conditions mean that a certain degree of mould growth in crawl spaces is unavoidable in exceptionally humid summers. (Kurnitski and Matilainen, 2000)

The growth of microbes is affected by nutrients, temperature, pH, oxygen, light and relative humidity, although in practice the relative humidity is the dominant factor. When the % RH is above 75% (ca 0 to + 50 C^o) mould growth is possible and even rot fungus can grow when the % RH is above 90…95 % (ca 0 to +45 C^o) (Viitanen et al., 2010). At low temperatures, however, (0 - 5 ^oC) mould growth is limited and mould does not grow at all when the temperature is below 0 ^oC (Ojanen et al., 2010). Each micro-organism has its own specific humidity and temperature requirements and microbial growth is also affected by the characteristics of the building materials and the duration of favourable growth conditions (Viitanen, et al., 2010). The result of microbial activity is that microbes and microbial metabolites are released from the crawl space structures and surfaces. In addition to the microbe sources on structures, radon flows into the crawl space, and microbes grow in the soil and on its surface so that gaseous microbial metabolites are released from the soil. Sub-floor leaks and depressurisation in the building increase the infiltration of air from the crawl space into the house. Fungal spores have been observed in crawl spaces that are tens of times above the concentration limits permitted in houses and flats. Colony-forming units of fungal spore concentrations of 10^3 – 10^5 cfu/cm^2 have typically been analysed from the surfaces in crawl spaces. Airborne spore concentrations of 10^3 – 10^4 cfu/m^3 have been measured in crawl space air when the conditions are favourable for such growth. As a point of comparison, the corresponding airborne spore concentrations measured in outdoor air are 10 – 1000 cfu/m^3. In winter, when the ground is covered with snow or is frozen, airborne spore concentrations may be less than 100 cfu/m^3 (Pasanen et al., 1990).

The microbial concentrations are higher in crawl spaces made of wood (Kurnitski and Pasanen, 2000). Microbial propagation with the airflow from the crawl space to the spaces above is affected by the pressure difference between the crawl space and the spaces above, and also by the points in the structures that are leaking air, and of course by the characteristics of the microbes themselves (Matilainen and Pasanen et al., 2002). The passage of particulate pollutants, such as fungal spores, through leaks into the house is a less well-known phenomenon than the passage of gaseous pollutants. The passage of particulate pollutants such as microbe spores and fungal mycelia depends on the size and aerodynamic properties of the particles, as well as the leakage geometry of the gaps. Fungal spore size varies by species. Estimating their passage from the crawl space is difficult because some of the fungi could be from indoors, while in summer outdoor sources are significant both indoors and in the crawl space. The properties of the leakage gaps in structures are difficult to specify and only theoretical permeability models have been developed. The size of fungal spores varies by species and is also affected by the growing conditions. Research carried out in Finland (sub-arctic climate), measured the microbe levels in crawl spaces, outdoor air and indoor air in summer and in winter. The results of this research, which was carried out at eight sites, showed that crawl space microbe levels are higher in summer than in winter. The ratio between the indoor air and the crawl space concentrations was the same or higher in winter than in summer. The correlation between the microbial concentrations in the crawl space and indoor air concentrations depends on the microbe species. At the sites measured, the most common fungus species were *Penicillium, Acremonium, Cladosporium* and yeasts. The correlation of concentrations of *Acremonium*, which does not have an internal source, in the crawl space and indoor air was high and thus indicated air leakage from the crawl space to the indoor air resulting from pressure difference (Airaksinen, 2003; Airaksinen et al., 2004 a).

In addition to spores produced by microbial flora, organic compounds from metabolic processes are released into the ambient air either directly from the surface flora or from within the damaged structure. The volatile organic compounds from these moulds are known to be unpleasant and, in combination with other indoor air factors, may cause symptoms of irritation for people in the building. VOC compounds may be released from undamaged building materials, and also as the result of human activity using detergents and chemicals. One of the problems in determining VOC compounds is also their sporadic release, which is a consequence of the changing growth conditions for the microbes. Volatile organic compounds travel with leakage air flow and can also travel and pass through materials by diffusion. **Publication V utilizes this approach**

2.7.4 Evaluation of the mould growth risk of a crawl space with the experimental Finnish mould growth model

The risk of mould growing on material is assessed using the mould growth risk calculation model developed by the Technical Research Centre and Tampere University of Technology, the "Finnish mould growth model". In this model, the risk of mould is calculated for different kinds of building materials based on changes in temperature and humidity. The calculation model is based on laboratory and field tests carried out on different materials. The Mould index rating is based on research which examined mould growth on the surface of pine and spruce (Viitanen, 1996; Viitanen and Ritschkoff , 1991; Ojanen et al., 2010). The Finnish mathematical model for mould growth is based on research (Hukka and Viitanen, 1999), and the model was later improved so that it covers most building materials (Ojanen et al., 2010; Viitanen et al., 2010). The values for the Mould index (M) given by the calculation do not describe the harmful effects of individual moulds, but rather the coverage of mould growth on a given surface material that is visually verified. The mould sensitivity classes of different materials are given in Table 2.

Table 2. Mould index for experiments and modelling of mould growth on building materials (Viitanen et al., 2011).

Mould index (M)	**Description of the growth rate**
0	No growth
1	Small amounts of mould on surface (microscopic), initial stage of local growth
2	Several local mould growth colonies on surface (microscope)
3	Naked-eye detection of mould on surface, <10 % coverage, or microscopic detection <50 % coverage of mould
4	Naked-eye detection of mould on surface, 10 – 50 % coverage, or <50 % coverage of mould (microscope)
5	Plenty of growth on surface, >50 % coverage visible to the naked eye
6	Heavy and tight growth coverage of approximately 100 %

The mould model calculates the critical relative humidity value (% RH_{crit}) for different temperatures which gives the conditions where mould growth is possible if a given material is subject to them for a sufficiently long time (Ojanen et al., 2010).

$$\% \ \mathrm{RH_{crit}} = \begin{cases} -0.00267\mathrm{T}^3 + 0.160\mathrm{T}^2 - 3.13\mathrm{T} + 100.0, \text{when } \mathrm{T} \leq 20 \\ \mathrm{RH_{min}}, \ \text{when } \mathrm{T} > 20 \end{cases}, (\mathbf{13})$$

where T = temperature (-)

$\% \ \mathrm{RH_{min}}$ = the lowest relative humidity value for a given material where mould growth is possible

For wood and wood-based materials $\% \ \mathrm{RH_{min}}$ is 80%. For other materials the factor must be determined separately.

A material's sensitivity to mould is taken into consideration when doing the calculation. The factors are determined based on the materials' sensitivity class for mould growth. Mould sensitivity classes for materials are determined based on laboratory and field tests. Based on mould sensitivity, materials are divided into four categories that take into account both the mould growth rate, and the maximum number of moulds. Table 3 shows the mould sensitivity classes for materials.

Table 3. Mould growth sensitivity classes and their material groups in research (Ojanen et al., 2010).

Sensitivity Class	Materials
1 Very Sensitive	Untreated wood; includes lots of nutrients for biological growth
2 Sensitive	Planed wood, paper-coated products, wool-based boards
3 Medium Resistant	Cement or plastic based materials, mineral fibre
4 Resistant	Glass and metal products, materials with efficient protective compound treatments

A safe limit value for a calculated crawl space Mould index is a value of < 1 (Ojanen et al., 2010) which was used in **Publication V**.

The mould growth rate $\frac{dM}{dt}$ is described in the mould model by the equation (Ojanen et al., 2010):

$$\frac{dM}{dt} = \left(\frac{1}{24}\right)\frac{1}{7\times\exp(-0{,}68\times\ln(T)-13{,}9\times\ln(RH)+0{,}14W-0{,}33SQ+66{,}02)}k_1k_2\ , \qquad \textbf{(14)}$$

where	T	=	temperature (-)
	k_1	=	factor (-) describes the intensity of mould growth **(Table 4)**
	k_2	=	factor (-) represents the moderation of the growth intensity when the Mould index level approaches the maximum peak value in the range of 4<M<6 **(15)**
	W	=	the timber species (0 = pine and 1 = spruce)
	SQ	=	surface quality (SQ = 0 for sawn surface, SQ = 1 for kiln-dried quality).

Ojanen has presented a more detailed description of factors k_1 and k_2 and their significance in mould growth modelling. The variable k_2 in the calculation takes into account the slowing of mould growth as the Mould index approaches its maximum value.

The factor k_2 that describes the evenness of mould growth is determined by an equation (Ojanen et al., 2010)

$$k_2 = \max[1-\exp[2.3\times(M-M_{max}],0]\ , \qquad \textbf{(15)}$$

In the calculation model, M_{max} represents the maximum Mould index value that can be achieved under different temperature and humidity conditions. In addition to them, the maximum level of mould growth depends on the material. The material is taken into account in the calculation by factors A, B and C.

The maximum value for mould growth M_{max} is calculated from the equation (Ojanen et al., 2010):

$$M_{max} = A + B\times\frac{\%\,RH_{crit}-RH}{\%\,RH_{crit}-100} - C\times\left(\frac{\%\,RH_{crit}-100}{\%\,RH_{crit}-100}\right)^2, \qquad \textbf{(16)}$$

where $\% \mathrm{RH}$ = relative humidity examined

A, B and C = factors (-) the coefficients A, B and C can have values that depend on the material class **(Table 4).**

Table 4. Parameters for the different sensitivity class (Ojanen et al., 2010).

Sensitivity Class	k_1		$k_2(M_{max})$		$\% RH_{min}$	
	M<1	M≥1	A	B	C	%
Very Sensitive	1	2	1	7	2	80
Sensitive	0.578	0.3886	0.3	6	1	80
Medium Resistant	0.072	0.097	0	5	1.5	85
Resistant	0.033	0.014	0	3	1	85

Mould declines as the temperature falls below 0 °C and the relative humidity falls below the critical humidity value, $\% \mathrm{RHcrit}$. The mould decline depends on the duration of the conditions unfavourable to mould growth.

For the reference material, for which pine or spruce are used, the mould decline $\frac{dM}{dt_0}$ is presented in the equation (Ojanen et al., 2010):

$$\frac{dM}{dt_0} = \begin{cases} -0.00133, \text{when } t - t_1 \leq 6h \\ 0, \text{when } 6h \leq t - t_1 \leq 24h \\ -0.000667, \text{when } t - t_1 > 24h \end{cases} , \tag{17}$$

where t_1 = start time of the unfavourable growth conditions (h)

t = time of unfavourable growth conditions (h)

The mould decline intensity $\left(\frac{dM}{dt}\right)_{mat}$ for each material being examined is calculated using the equation (Ojanen et al., 2010):

$$\left(\frac{dM}{dt}\right)_{mat} = C_{mat} \left(\frac{dM}{dt}\right)_0 , \tag{18}$$

where C_{mat} = the relative coefficient for Mould decline in the simulation model (Table 4).

In the calculation model, the mould decline is broken down into categories according to the material's mould sensitivity categories. The mould decline is taken into account by the decline factor C_{mat} in Table 5.

Table 5. Classification of relative mould decline (Ojanen et al., 2010).

Sensitivity Class	Description	C_{mat}
Very Sensitive	Significant relevant decline	0.5
Sensitive	Relative low decline	0.25
Medium Resistant and Resistant	Almost no decline	0.1

In Publication V, a hygrothermal simulation allowed the study of the temperature and humidity conditions as well as mould sensitivity in open and closed ground structure crawl spaces over a period of two years. The Finnish mould growth model, which was specifically designed for this purpose, was used in the assessment of mould growth on different building materials. **In Publication V** the mould risk in a depressurised, ventilated crawl space is examined with two different mould sensitivity classes: Very Sensitive and Medium Resistant. In practice, an externally ventilated crawl space contains contaminants, such as dust and pollen carried in by the infiltration air. Organic dust on the surface of the material increases the risk of mould growth (Viitanen et al., 2010). Therefore, the risk of mould growth in the crawl space should also be examined in the mould sensitivity class Very Sensitive.

2.8 Open questions based on the summary of the literature

The effect of barometric pressure, rain and wind has been examined in several studies with varying results (Nazaroff et al., 1985 and 1988; Hintenlang and Al-Ahmady, 1992; Robinson et al. 1997, Riley et al. 1996, Arvela et al. 1994 and 2015, Breitner et al,. 2010). However, the effects that rain and changes in barometric pressure have on the leakage of soil air and the generation of radon through structures touching the ground have been little studied in Finland.

According to research by the Radiation and Nuclear Safety Authority and Helsinki University of Technology, air change was, on average, higher in houses with mechanical ventilation than in houses built in the same way, but with natural ventilation. However, the radon concentration was on average slightly higher in houses with mechanical ventilation (Ruotsalainen et al., 1997, Arvela, 1995 b). By repairing and regulating mechanical ventilation and installing a supply and exhaust ventilation system, a reduction in radon concentrations of 35-80% was achieved. The best results were achieved using supply and exhaust ventilation, with the supply air regulated at a maximum of 10% less than the exhaust air to minimize depressurisation (Keskinen et al., 1989). In research by the Radiation and Nuclear Safety Authority, the use of mechanised supply and exhaust ventilation reduced the radon concentration by 20% to 80% (Hoving et al., 1993). Given the significant difference between the level of depressurisation caused by exhaust ventilation and supply and exhaust ventilation systems, it is likely that the switch to supply and exhaust systems in semi-detached and row houses must have contributed to the reduction in radon concentrations in row houses and in the whole stock of detached houses (Arvela et al., 2010). In terms of results, it is important that the ventilation is technically correctly implemented, and there is continuous use of efficient ventilation.

Several questions arose in relation to the results presented: Can we statistically predict the radon entry rate into houses by measured physical and environmental factors, and what are the factors influencing the results? How do wind direction and speed affect radon entry rate and what is the coefficient of determination? How do rain and measured changes in barometric pressure affect the radon entry rate? What are the pressure differences in supply and exhaust ventilated houses and what is the effect of using an attic space as the external measuring point for the pressure difference? What are the different factors influencing the pressure difference indoors, and what is the effect of the internal airflows caused by the ventilation between different spaces? What benefits and drawbacks can be obtained if the pressure differential is controlled by mechanical ventilation?

Crawl space depressurisation has been found to reduce indoor radon in the range of 70% – 96%. Crawl space pressurisation has been found reduce indoor radon in the range of 30% – 80% (Henschel, 1992). Fungal spores have been observed in crawl spaces that are ten times higher than the concentration limits permitted by Finnish building regulations (Pasanen et al., 1990). The results of theoretical calculations of the indoor air concentration of selected VOCs revealed that microbial growth in construction seems to have only a marginal effect on the total VOC load in indoor air (Pasanen et al.

1998). Several questions arise in relation to the results presented. How do different ventilation solutions affect the radon, microbial and MVOCs concentration in a house with a crawl space? How well can different ventilation systems maintain crawl space depressurization relative to indoors?

There hadn't been any previous studies taking into account the effect of depressurization of crawl spaces, so Airaksinen and Kurnitski (2003; 2000) have modelled the conditions in non-depressurized ventilated crawl spaces. Several questions arose in relation their results. Can a crawl space with uncovered ground be kept depressurized with moderate exhaust ventilation airflow?

Long-term 70–90% relative humidity has been observed in numerous studies of crawl spaces, (Kurnitski et al. 2000; Samuelsson 1994; Johansson et al, 2013; Iwamae et al. 2003; Laukkarinen et al. 2017). According to Matilainen and Kurnitski (Kurnitski et al. 2000; Matilainen et al. 2003)], humidity problems in crawl spaces can be reduced by heat insulation of the cold ground in the crawl space and by ensuring basic ventilation 0.5–1 h^{-1}. In cases where the bottom of the crawl space is covered by a layer of crushed gravel as a form of evaporation insulation, it is recommended that in summer ventilation should be increased to the value of (2-5 h^{-1}) (Kurnitski et al. 2000). Because there is always enough organic material in a crawl space for mould to feed on, the conditions are favorable for the start of mould growth (Viitanen et al. 2010; Gradeci et al. 2017).

Several questions arose in relation to the results in the literature. What are the effects of exhaust ventilation and different construction materials on hygrothermal conditions and on the sensitivity to mould growth in a crawl space with an open base of uncovered ground compared to one with air-sealed ground structures? What could be recommended for the structures, materials and ventilation in a crawl space to make it microbiologically safe?

3 The aims of this study

The detailed aims of the study were:

1. to statistically examine the effect of measured environmental conditions on the indoor radon concentrations in seven detached houses (Publications I-V).

2. to examine the capability of mechanical supply and exhaust ventilation to reduce the radon concentration in indoor air (Publication IV).

3. to examine the factors that affect the pressure differences and the internal air flows in a detached house equipped with mechanical supply and exhaust ventilation. To assess the capability of continuous adjustment of the pressure difference in buildings with different airtightness (Publication IV).

4. to investigate how ventilation of the crawl space will influence concentrations of radon, fungal spores and MVOCs in the crawl space and indoors in a detached house. (Publication V).

5. to examine computationally the convective flow through the crawl space with a gravel-filled foundation structure whose gravel fillings are of two different permeabilities, and to evaluate the ability of exhaust ventilation to maintain depressurisation in the crawl space. To make recommendations on depressurising a crawl space using exhaust ventilation (Publication V).

6. to examine by computational modelling the effect of different factors (the airtightness, ventilation and construction materials of open and airtight crawl spaces, depressurised by exhaust ventilation), on the temperature and humidity conditions and on the sensitivity to mould growth in the crawl space during two test years with critical outdoor air conditions. To make recommendations for crawl space structures and materials and their ventilation (Publication V).

4 Materials and methods

This chapter presents an overview of the study material and methods used. Detailed descriptions are presented in **Publications I-V**.

4.1 Buildings studied

The subjects selected for the research project were seven detached houses with indoor radon concentrations in excess of the Finnish Ministry of Social Affairs and Health’s guide value of 400 Bq m^{-3}. In terms of their construction and location, the sites were very typical of the Finnish detached housing stock. The research sites differed from one another in terms of the number of storeys, the foundation type, the surrounding terrain, soil quality and permeability, the airtightness of the buildings and the radon levels in the interior rooms. The houses are located in three different regions in southern Finland: House A in Rekola (**Publications I-IV**), Houses B-F in Hollola (**Publications I-IV**) and House G in Tampere (**Publication III-V**). The radon concentrations in the houses were measured before installation of the new ventilation system using the Radiation and Nuclear Safety Authority’s integrating film method. The concentrations measured are presented in Table 6.

Table 6. Indoor radon concentration (Bq m^{-3}) in the seven houses (A-G) before mitigating measures were taken. The number of measurements is given as long-term (alpha track detector) concentrations of indoor radon (Rn).

<table>
<tr><th rowspan="2">Factors</th><th colspan="7">Houses</th></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td><td>F</td><td>G</td></tr>
<tr><td>$n_{50\ Pa}$ (h^{-1})</td><td>8.6</td><td>3.6</td><td>5.8</td><td>6.0</td><td>3.6</td><td>3.1</td><td></td></tr>
<tr><td>Storey</td><td>1</td><td>2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Location</td><td>Helsinki</td><td>Hollola</td><td>Hollola</td><td>Hollola</td><td>Hollola</td><td>Hollola</td><td>Tampere</td></tr>
<tr><td>Terrain</td><td>frs</td><td>Ge</td><td>Ge</td><td>Ge</td><td>Ge</td><td>Ge</td><td>llcs</td></tr>
<tr><td>Foundation</td><td>gscs</td><td>basement+ gscs</td><td>gscs</td><td>gscs</td><td>gscs</td><td>gscs</td><td>crawl space</td></tr>
<tr><th colspan="8">Initial condition, original ventilation</th></tr>
<tr><td>Ventilation type
Rn (Bq m^{-3})
Ventilation time</td><td>Natural
850
(24h/d)</td><td>Ex
2931
(0h/d)</td><td>Ex+Su
2780
(1h/d)</td><td>Ex+Su
1520
(4h/d)</td><td>Ex+Su
1020
(18h/d)</td><td>Ex+Su
-
-</td><td>Ex+cs+p
25
(24/d)</td></tr>
<tr><th colspan="8">Before mitigation, intensify ventilation</th></tr>
<tr><td>Ventilation type
Rn (Bq m^{-3})
Ventilation time</td><td>Ex+Su+Ca
630
(24h/d)</td><td>Ex
3080
(0h/d)</td><td>Ex+Su
795
(24h/d)</td><td>Ex+Su
870
(24h/d)</td><td>Ex+Su
630
(24h/d)</td><td>Ex+Su
845
(24h/d)</td><td>Ex+cs+p
-
-</td></tr>
</table>

Ex+Su = old combined exhaust and supply ventilation with kitchen fan, Ex = old exhaust ventilation, Ex+Cs+p =original exhaust ventilation, crawl space pressurised by exhaust, Ca = circulation air, h/d = operating time per day, and ($n_{50\ Pa}$) = airtightness, gscs = ground-supported concrete slab, Ge = gravel esker, frs = fragmented rock soil, llcs = low-lying clay soil and h/d = operating time per day.

4.1.1 Building and location information, house A

This building is located on a fragmented rock soil with a slight slope to the south, and is a detached house with a ground-supported concrete slab foundation and gravel fill. Expanded clay blocks were used in the foundations and the house has brickwork cladding. The building has a sloping roof and a cold ventilated attic space. The attic is ventilated by ventilation gaps under both eaves. There is an un-heated garage at the western end of the building. The residential part and the garage dividing wall also divides the attic space into two areas. The height of the terrain surrounding the building is variable and it is also sheltered by trees. Radon concentrations at the site were measured before installation of the new ventilation system using the Radiation and Nuclear Safety Authority's integrating film method (Table 6).

4.1.2 Building and location information, houses B-F

Buildings B-F are located on the same gravel esker in Hollola. Building B is two storeys and buildings C-F are single-storey detached houses with ground-supported concrete slab foundations and gravel fill. Expanded clay blocks were used in the foundations and the houses have plastered brickwork cladding. All of the buildings have a sloped roof and an undivided ventilated, cold attic space. The buildings' load-bearing structures are wood. The attic is ventilated by ventilation gaps under the eaves. The buildings also have garages attached. The load bearing external wall in the basement of building B is made of expanded clay blocks. Radon concentrations at the sites were measured before installation of the new ventilation system using the Radiation and Nuclear Safety Authority's integrating film method (Table 6).

4.1.3 Building and location information, house G

This research site is a single-storey detached house, which is located on low-lying, clay soil. Below the building is an undivided crawl space. The crawl space subsoil is covered with perforated plastic film with a layer of sand on it. Expanded clay blocks have been used for the building's foundations and the sub-floor is made of light cement elements. The site has exhaust ventilation, which was intended both to combat radon and for crawl space heating. In this method, exhaust air is fed to the crawl space by the house's exhaust fan. In this way, the over-pressurised crawl space (52 m^3) was ventilated to the outside via an open-air ventilation duct. Radon concentrations at the sites were measured before installation of the new ventilation system using the Radiation and Nuclear Safety Authority's integrating film method (Table 6).

4.2 Ventilation systems of the buildings studied

4.2.1 Ventilation system

The old ventilation systems were removed from sites A-F and replaced with ventilation units suitable for controlling pressure differences (Publication IV). The ventilation systems were adjusted to meet the new ventilation regulations and operating instructions. The new ventilation unit differs from the standard unit in that both the ventilation fans' power can be controlled. Both of the unit fans (supply and exhaust) have a voltage regulating unit for each fan. The ventilation unit consists of a supply and exhaust fan, heat recovery cell, after-heating coil, mechanical filters and an electrical filter for supply air and automation. Frost prevention is achieved by by-passing the heat recovery cell so that supply air flow does not have to be stopped. A DDC regulator used in building automation was installed in the ventilation unit to control the pressure difference. It can also be used to collect information from the appropriate measurement points.

After installation of the equipment, supply and exhaust air flows were measured for each room and were adjusted to comply with (D2), the design values. The flow surface areas of the transfer routes between rooms correspond to the existing guidelines and no changes had to be made to them.

4.2.2 Operation of the system

Using the fans in a mechanical supply and exhaust ventilation unit and pressure difference regulation enabled depressurisation or overpressure to be maintained continuously inside the building with as low as possible depressurisation or overpressure. The operation of the ventilation unit has been presented earlier in a published article (Kokotti et al., 1994). The system tries to keep the pressure difference within specified values as the factors that affect the pressure difference change with changing ventilation power and, for example, if the cooker's extractor hood is used. Ventilation that meets the norms must be guaranteed in all airflow regulation conditions and therefore the regulator has tolerance limits for the fluctuation in airflows.

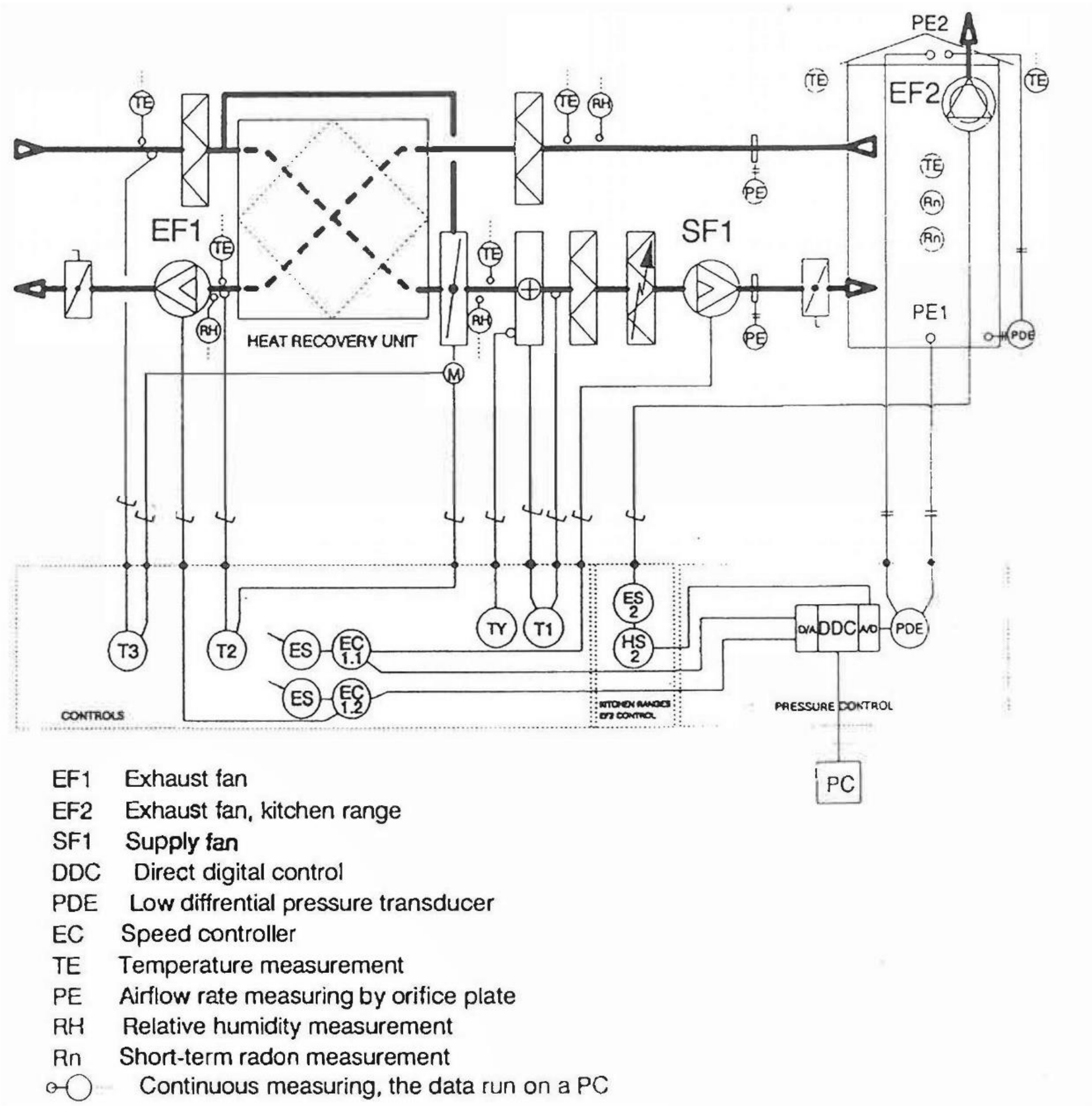


Figure 2. The principle of the continuous adjustment and control system for the indoor-outdoor pressure difference (Kokotti et al., 1994)

The pressure control (PC) alters the amount of air through the supply and exhaust fans (EF1 and SF1) on the basis of measurements from the pressure difference sensor (PDE) so that the pressure difference in the building is maintained at the differential pressure control (PC) set point. Regulation is achieved through the pressure controller's by-pass messages (control messages vary between 0...10V) changing the fans' voltage regulator's output voltage over ten levels. Changing the output voltage causes a corresponding change in the fan speed, and thus the airflow. As depressurisation increases the power of the supply air fan increases. The exhaust fan power decreases if the supply air fan power is insufficient. As depressurisation decreases the opposite occurs.

The pressure control can be used to limit the range of fluctuation in the pressure controller's air volume. This is achieved by setting the control at different settings for supply and exhaust across a sliding scale of values for different ventilation powers. The sliding values can be used to define the limits within which the pressure control can change the flow through the supply and exhaust fan at different ventilation powers. If the pressure difference measured shows a pressure more than the pressure control set value, the unit changes the air flow within the sliding scale limits set for the pressure difference between the supply and exhaust airflows (the duct regulators are used to set the exhaust higher than the supply air).

The appropriate ventilation power is controlled by a separate switch (0... 100%, which corresponds to the control message 0... 10 V). The pressure control has a switch that allows the pressure difference control to be switched off, and then the supply and exhaust air ventilation system sets the selected ventilation option and the fan voltage regulator control message is the same for each fan. When the cooker's extractor hood (EF2) is being used, the pressure control adjusts the room pressure difference immediately and the fluctuation in the amount of air may exceed the limits, or a lower limit can be set for the exhaust air. A pressure difference set point can be set specifically for when the extractor hood is on. This system can also be used to set timings for the pressure difference settings. A control can be used to change the pressure difference setting values, the measurement time, the control actuation time and the air flow fluctuation range. Correction of the pressure difference control's neutral point can be done with the maintenance software on a normal PC.

4.3 Measuring system of the buildings studied

Measurement periods were divided into those in which the pressure difference control was in use and periods when it was not. The length of a measurement period varied from one to two weeks. In order to enable comparison between the periods, the dimensional output of the system was regulated using the regulating vents and valves in the supply and exhaust ducts to be depressurised, so the exhaust air flow was greater than the supply air flow. When the pressure difference control is switched off, the air flows are determined by the total air flow settings where the exhaust air is greater than the supply air.

In this study, the pressure difference control periods were treated as one long measurement period. In this way, the effect of different variables on radon source strength can be examined with more materials and a wider measurement range.

Measurement data were collected from 25 measuring points. The measurement points and their locations are shown in the Kokotti et al., 1994 publication. Data was collected on the operation of the ventilation unit, the operation of the pressure difference control, from the rooms and from a local weather station. The measurement points were connected to the DDC controller from which a history collection programme collected data onto the hard disk of a micro-computer connected to the system. The data collection measurement interval was 5 min during all measurement cycles. In the final measurement file, measuring point data was converted into hourly average values.

4.3.1 Measurements

The indoor and outdoor air pressure difference was measured at two separate points. The pressure difference between the living room and the attic was used as the regulating pressure difference for the ventilation unit. The internal measurement point was on the wall, about 20 to 40 cm from the floor. The measurement point in the attic was in the middle of the attic about 20 cm above the insulation layer. The measuring point on the external wall was located on the centreline at the level of the eaves.

The low-pressure difference transducer's (Setra 264) pressure measurement range was $\pm$25 Pa. The pressure transducer error was $\leq$1% (fs). After each measurement cycle, the stability of the pressure difference transmitter's zero differential pressure was checked and, if necessary, the result of the measurement was corrected using the pressure difference control software.

The weather station (R. Rehn Ky) sensors were placed on a tubular mast approximately 2 m above the ridge to the east of the building. The equipment consisted of a wind speed sensor, wind direction sensor, a transmitter for these measurements and an outdoor temperature sensor placed inside a radiation shield. The temperature was measured in the bedroom and living room about 1.1 m from the floor.

The ventilation units' supply and exhaust air flows were measured using measuring elements installed in the supply and exhaust air ducts. The measurement method error was ≤5%.

Short-term radon level fluctuations were monitored continuously using a portable Pylon AB-5 measurement and data storage device (Lucas, 1957) (**Publication I-V**). The AB-5 has an internal battery, air pump, photomultiplier tube and the electronics needed for measurement and data storage. The device's detector was a LUCAS scintillation cell 300 A. The measurement interval length was half an hour. The long-term concentration of radon was measured in the same rooms as the short-term measurements. The long-term radon is determined by using alpha track detectors. The detectors were analysed by nuclear track dosimeters at the Finnish Radiation and Nuclear Safety Authority (STUK) (**Publication I-V**). The analysis method is based on a German system and was modified for STUK

Radon concentrations were measured in the living areas, i.e. the bedrooms and living rooms. At site B, the radon concentration was measured from a downstairs living room with a fireplace.

With regard to radon generation, relevant data on atmospheric pressure and rainfall were provided by the Finnish Meteorological Institute. Data for site A were collected from Helsinki-Vantaa Airport and for sites B to F data came from the Lahti measurement station. There was no significant change in atmospheric pressure values over such a short distance between the measurement point and the research site (Hintenlang and Al-Ahmady, 1092, originally Blair and Fite, 1965).

The Finnish Meteorological Institute's weather observations were three-hour averages. Rain data was measured every 12 hours. Rain data was checked from the 17 May, after the soil had thawed.

Indoor airflow and infiltration were measured twice in houses E and F (**Publication IV**) by using an integrated tracer gas method (Dietz et al., 1985) and a three-zone model. Two- and three-zone models were used to analyse the result of the tracer gas measurement. This method was developed at Helsinki University of Technology (Säteri et al., 1989 and 1991).

Passive tracer gas devices were distributed in the living room, kitchen, bedrooms, bathroom and toilet. Sampler devices were distributed in the bathroom, toilet and walkin closet. The tracer gas devices are filled with tracer liquid, which is dispensed as any of three tracer gases at an essentially constant rate. With this passive tracer gas method (PFT) three different perfluorocarbon types were used as tracers: perfluoromethylcyclohexane (PMCH), perfluoromethylcyclopentane (PMCP) and perfluorodimethylcyclohexane (PDCH) – one in each ventilation zone. Separate PFD-sampler devices collected air samples by diffusion into an absorbent material. The sampler absorbs the tracer gas at a rate that is proportional to its concentration. These PFD-samplers were returned to the laboratory for analysis at the end of the week-long measurement period. The PFC-samplers were analysed using gas chromatography (GC) at Helsinki University of Technology.

In addition to the PFT-measurements, mechanical supply and exhaust flow rates were also determined simultaneously during the PFT-measurement.

The airtightness of the houses (A-G) were determined using the blow-door depressurisation test (**Publication I-V**). The negative pressure was increased in stages up to 50 Pa and airflow was measured (EN 13829, 2000). According to estimates, the accuracy of the measurement results of the pressurisation test is within ±10…15 % (SS 02 15 51, 2000 and EN 13829, 2000). The airflow required to maintain a pressure difference of 50 Pa could be calculated by equation (17). Thus, the air change rate at 50 Pa can be calculated as:

$$n_{50\ \mathrm{Pa}} = \frac{Q_{50\ \mathrm{Pa}}}{V}\ , \qquad \textbf{(19)}$$

where $n_{50\ Pa}$ = airtightness, air change rate at 50 Pa (h^{-1})
$Q_{50\ Pa}$ = air flow at 50 Pa (m^3h^{-1}) **(8)**
V = volume of the building (m^3)

4.4 Formation of data and data analysis

4.4.1 Formation of data

Average measurement data collected at 5-minute measurement intervals was converted to one hour, three hour and eight hour averages. The following variables (*m*), used in the analyses were entered into the observation matrix, as shown in Table 7:

Table 7. Variables.

Label	**Variable**	**Value**	**Unit**
T2	time of day	0,00…1,00	-
PDin-out	pressure difference between indoor and outdoor air	±0,0…	Pa
Tin-Tout	temperature difference between indoor and outdoor air	±0,0…	^{o}C
Ws	wind speed	0,0…	$m\ s^{-1}$
Wd	wind direction	1,2,3...8	-
Rain	rain data	0,1,2 and 3	-
AP	air pressure	0…	hPa
S	radon source strength	0…	$Bq\ m^{-3}\ h^{-1}$

Formation of observation matrix variables

T2 = time of day

The time of day in hours 0-23 time were scaled to numeric values between 0 and 1

Wd = wind direction

Wind direction was formed as shown in Table 8:

Table 8. Formation of wind variables.

Wd	Wd °	Wd label
north	$22.5^{o} \geq Wd > 337.5^{o}$	8
north-west	$292.5^{o} < Wd \leq 337.5^{o}$	7
west	$247.5^{o} < Wd \leq 292.5^{o}$	6
south-west	$202.5^{o} < Wd \leq 247.5^{o}$	5
south	$157.5^{o} < Wd \leq 202.5^{o}$	4
south-east	$112.5^{o} < Wd \leq 157.5^{o}$	3
east	$67.5^{o} < Wd \leq 112.5^{o}$	2
north-east	$22.5^{o} < Wd \leq 67.5^{o}$	1

Rain:

The amount of rain (mm) was changed to the following:

0 = no rain, 1 = before rain, 2 = after rain and 3 = rain

Radon entry rate S (Bq m^{-3} h^{-1}) was calculated using the variable for air volume Q_t (m^3 h^{-1}), the radon concentration variable Rn_i (Bq m^{-3}) and the volume data V (m^3), according to the equation:

$$\mathrm{S} = \mathrm{Rn_i} \times \frac{\mathrm{Q_t}}{\mathrm{V}}\ (\mathrm{Bq\ m^{-3} h^{-1}}) \quad , \tag{20}$$

The radon entry rate value S was calculated using the supply airflow as the air volume variable.

4.4.2 Data analysis

The material was analysed using SPSS / PC+ statistical software, version 5.0.2. (Norusis, 1990).

The linear dependency of the variable pairs was examined using the Pearson correlation coefficient.

Linear regression analysis was used to examine the simultaneous effect and dependency of physical factors on the radon entry rate S1 (Bq m^{-3} h^{-1}). A stepwise regression model was used in which the best explanatory variable was selected first on the basis of the statistical significance of the correlations. The following variables were selected based on the correlations of the regression residuals, and variables below the significance limits were deleted from the model. The significance limit when selecting the model was $p \leq 0.05$ (known as the PIN value) and the significance limit for deletion from the model was $p \geq 0.10$ (known as the POUT value). The summary of the regression analysis presents the correlations, the coefficient of determination and significance tests as well as the multiple regression correlation coefficients that were taken into the model at each step. The quality of the model was checked by examining the regression analysis residual. The normal distribution of the variables included in the model was examined graphically. (Armitage, 1994).

Between the explanatory variables of this study, there is a physical dependence, which can be examined using physical calculation models. Using these models, radon entry rate can be defined through calculations from several explanatory variables physically calculated using pressure difference. Using linear regression analysis, it is possible to examine the effect and structure of the dependence of the building's measured pressure difference, and other measured explanatory variables, on radon source strength. This requires an adequate coefficient of determination, residual analysis and clear statistical significance.

In variance analysis, the fluctuation of the explanatory variable, for example radon entry rate S1 (Bq m^{-3} h^{-1}) is divided into the fluctuation that the joint impact of the grouped variances explains as well as the residual fluctuation that the grouped variables are not able to explain. This fluctuation is measured using variance analysis. Covariates can be included in the variance analysis and the result will then give standardised averages with respect to the covariates (Armitage, 1994).

Covariance analysis was used to examine the effect on the radon entry rate S1 of the time of day T2, wind direction Wd, and rain. The analysis was used to calculate the group averages S1 of a group variable and the covariate corrected group average S1 deviations from the total average. Group variables were time of day T2, wind direction Wd and rain. The variable T2 used in the analysis is a quasi-variable, which is not included in the physical model presented.

5 Results

An overview of the results is presented in Publications I-V. Additional unpublished results are also included in this thesis.

5.1 Radon

5.1.1 The effect of different factors on indoor radon

The impact and dependence of physical and meteorological factors on the radon entry rate (Bq m^{-3} h^{-1}) in a detached house was examined using linear regression analysis. Houses (B-F) were constructed on the ground on an esker, house (A) was constructed on fragmented rock and house (G) has a crawl space and is constructed on low-lying, clay soil (**Publication I-V**). The explanatory factors for radon entry rate were the indoor-outdoor pressure difference, indoor-outdoor air temperature difference, wind direction and speed. In addition, at two sites (A and B), the effect of atmospheric pressure, rain and time of day, (used as a quasi-variable), on radon source strength was examined. The effect of the wind direction and rain on radon entry rate and indoor radon concentration were examined using covariance analysis where the covariates were temperature difference, wind and pressure difference.

The most important explanatory factors for radon entry rate at the research sites after the installation of the new ventilation system are presented in Table 9.

In the correlation analysis between pairs of variables at each house, the radon entry rate correlated most strongly with the temperature difference and pressure difference. The correlations fluctuated between a correlation of 0.32 at site G with its crawl space and a correlation of 0.75 for house A built on the ground. Other factors only had a slight impact on the correlation and coefficient of determination. The coefficients of determination fluctuated between 7% at house G (with a crawl space) and 53% for house A, built on the ground. The most important explanatory factors for radon entry rate at the studied houses proved to be temperature difference and pressure difference. For house G, with its crawl space, the most important factor for radon entry rate proved to be the pressure difference between the crawl space and the outdoors with a coefficient of determination of 87%.

Table 9. The effect of pressure difference ($PD_{in\text{-}out}$), temperature ($T_{in\text{-}out}$), wind (Ws) and time of day (T2) on radon entry rate after the installation of the new ventilation system.

House A	Multiple R	R Square change	BetaIn	Variable
n of cases=3616h	0.73	0.53	0.73	$T_{in\text{-}out}$
	0.74	0.55	-0.16	T2
	0.75	0.57	-0.14	$PD_{in\text{-}out}$
	0.75	0.57	-0.04	Ws
House B n of cases=1131h	0.53	0.28	-0.53	$PD_{in\text{-}as}$
	0.54	0.29	-0.11	T2
	0.54	0.29	-0.16	$PD_{in\text{-}out}$
House C n of cases=471h	0.56	0.31	0.56	$T_{in\text{-}out}$
	0.57	0.33	-0.13	Ws
	0.59	0.35	0.25	$PD_{in\text{-}out}$
House D n of cases=638h	0.29	0.09	0.29	Ws
	0.46	0.21	0.41	$T_{in\text{-}out}$
	0.47	0.22	-0.08	$PD_{in\text{-}out}$
House E n of cases=1215	0.69	0.47	0.69	$T_{in\text{-}out}$
	0.77	0.59	-0.32	$PD_{in\text{-}out}$
	0.78	0.61	0.17	Ws
House F n of cases=808h	0.50	0.25	-0.50	$PD_{in\text{-}out}$
	0.67	0.45	0.45	$T_{in\text{-}out}$
	0.68	0.50	-0.50	Ws
House G n of cases=375h	0.27	0.07	-0.27	$PD_{in\text{-}out}$
	0.29	0.09	-0.16	AP
	0.32	0.10	-0.14	Ws
House G crawl space n of casse=375h	0.87	0.75	-0.89	$PD_{in\text{-}out}$
	0.89	0.79	-024	AP

Multiple R = multiple regression, R Square change = coefficient of determination, BetaIn = standardized coefficient for mutual comparison of the explanatory variables

5.1.2 Effect of wind on indoor radon

The average indoor radon concentration varied strongly (100 Bq m^{-3} - 603 Bq m^{-3}) in the houses (C - F), which were located on top of the same esker, despite their effective and similar ventilation rates. The ventilation rate Q exceeded 0.5 h^{-1} in all houses except house G, where the ventilation rate was 0.35 h^{-1}. The airtightness values were in general representative of old Finnish single-storey detached houses (Kauppinen, 2001; Vinha J. et al., 2015)) except for house A which had an airtightness value as high as 8.6 h^{-1}. The measurement results are presented in Table 10 (Table 1 in **Publication III**).

Table 10. The table gives mean values and standard deviation (s.d.) of hourly measurements of radon (Rn), the difference in indoor-outdoor pressure ($P_{din\text{-}out}$), the difference in indoor-outdoor temperature ($T_{in\text{-}out}$), the mechanical ventilation rate λ_{bmw}, the wind speed (ws). The number of measurements is given as measurement time (n). The airtightness ($n_{50\ Pa}$) is also given (Keskikuru, et al., 1999).

Factors	**Houses**							
	A	B	C	D	E	F	G(in)	G(cs)
n (hour)	3616	1131	471	638	1215	808	375	375
Rn (Bq m^{-3}) s.d. (Bq m^{-3})	173 81	603 134	572 212	297 161	340 220	100 56	22 8	755 164
$PD_{in\text{-}out}$ (Pa) s.d. (Pa)	0.2 0.4	1.2 0.9	1.5 1.3	0.8 0.9	0.9 0.5	1.9 1.1	-0.2 0.6	-2.9 3.2
λ_{bmw} (h^{-1}) s.d. (h^{-1})	0.51 0.07	0.57 0.04	0.55 0.07	0.72 0.09	0.61 0.15	0.55 0.05	0.35 0.01	2.24 0.57
$T_{in\text{-}out}$ (^{o}C) s.d. (^{o}C)	10.1 7.6	29.4 4.3	28.5 7.9	21.4 5.8	23.8 7.5	17.0 4.7	16.0 3.4	7.0 2.9
Ws (m s^{-1}) s.d. (m s^{-1})	0.5 0.5	1.0 0.8	0.7 0.7	1.2 0.8	1.3 0.9	0.9 0.3	1.1 1.0	1.1 1.0
$n_{50\ Pa}$ (h^{-1})	8.6	3.6	5.8	6.0	3.6	3.1	3.1	-

The effect of the wind increases depressurisation inside the building, and thus the radon entry rate may increase. However, wind also increases uncontrolled ventilation, and thus indoor radon concentration falls. The wind effect was examined using linear regression analysis and the effect of wind direction on radon concentration was further examined in more detail using covariance analysis (**Publication III)**. The variables used as covariates were indoor-outdoor air pressure difference, indoor-outdoor air temperature difference, wind direction, ventilation and a time factor used as a quasi-variable. The dependence of the concentration of indoor and crawl-space radon on the wind direction was investigated by the analysis of covariance, by which the deviations of the adjusted group means (wind direction 1 to 8, v≥0.4 m s^{-1}) from the grand mean were also calculated. A wind direction is a circular function with a crossover point between 360^{o} and 0^{o}; therefore, standard statistical methods for linear data sets are not applicable for it, but the Yamartino method was used when the arctangent of the mean sines and cosines was calculated (Turner, 1986).

Table 2 of **Publication III** shows the dependence of the indoor radon concentration on the wind direction in the houses A-G. Figures 1-4 of **Publication III** show the dependence of the measured concentration of indoor radon on wind direction in houses A-G.

The first region (A); In the ground-supported concrete slab house, A, fluctuating wind had no significant effect because the house is located on a gently sloping rocky surface. The coefficient of determination increased slightly, and the concentration of indoor radon decreased slightly when the average wind speed increased. The coefficient of determination increased smoothly to give the highest coefficient of determination for the material (72%) when the wind speed increased to a speed of $v \geq 0.6$ m s^{-1}. On the other hand, the wind direction did not affect the coefficient of determination. According to the analysis of covariance the highest concentration of indoor radon (19% over the grand mean) was observed when the wind came from a certain direction and probably induced the transport of radon from the unventilated garage through the wall or floor structures to the adjacent living space.

The second region (B); in the basement house B, the highest concentration of indoor radon (+27% over the grand mean) and the highest coefficient of determination was observed when the wind direction was perpendicular to the esker, leading to increasing pressure from soil gas and consequently to increased radon entry. The lowest concentration of indoor radon, (-33 % under the grand mean) was observed when the wind was blowing from the top of the esker. When the wind was blowing in this direction it had no strong effect on the flow in the slope of the esker and on possible increases in the concentration of indoor radon in the basement rooms, which were depressurised. The concentration of indoor radon and the coefficient of determination increased slightly when the average wind speed increased, but the coefficient decreased at high wind speeds.

In the case of the ground-supported concrete slab houses C... F, which were located on top of the same esker, the highest concentration of indoor radon (+20 to +33% higher than grand mean) and the highest coefficient of determination (0,28 to 0,71) occurred when the wind was blowing perpendicularly to the south slope of the esker (on the opposite side to house B). There were other buildings and asphalt-covered roads on the south slope of the esker and the topography of the terrain was varied. The lowest concentration of indoor radon, (-22 to -44 % under the grand mean) was observed when the wind was blowing parallel (west-east directions) to the esker.

The third region (G); in the crawl-space house, the wind speed was not found to influence the concentration of indoor radon but the concentration of indoor radon was higher (+12% over the grand mean) in the crawl-space when the wind came from shielded directions. The radon concentration in the soil near the house probably decreased when the wind came from these wind directions. The radon concentration in the crawl-space was high but the indoor concentration of radon was very low due to the effective and correctly adjusted supply and exhaust ventilation in the crawl-space and indoors.

5.1.3 Diurnal variation

The impact of the time of day was investigated in two houses (A and B) (**Publications I and II**). The variables used as covariates were in indoor-outdoor pressure difference, indoor-outdoor air temperature difference, wind direction and speed. The analysis was used to calculate the group averages of the time of day and the covariate corrected group average deviations from the total average. Site A results are presented in Figure 3 (Figure 5 in **Publication II**). The largest covariate-corrected values for the radon entry rate S1 (Bq m^{-3} h^{-1}) were observed between 07.00 and 09.00, when the average values for temperature difference, wind speed and pressure difference were 14.3 ^{o}C, 0.38 m s^{-1} and 0.27 Pa. The lowest values were observed between 22.00 and 24.00 when the average values of the same variables were 14.4 ^{o}C, 0.23 m s^{-1} and 0.07 Pa respectively. The highest source strength values at the site built on the esker were observed between 23.00 and 10.00 and the lowest between 10.00 and 23.00. However, the deviations of radon entry rate from the total average were minor.

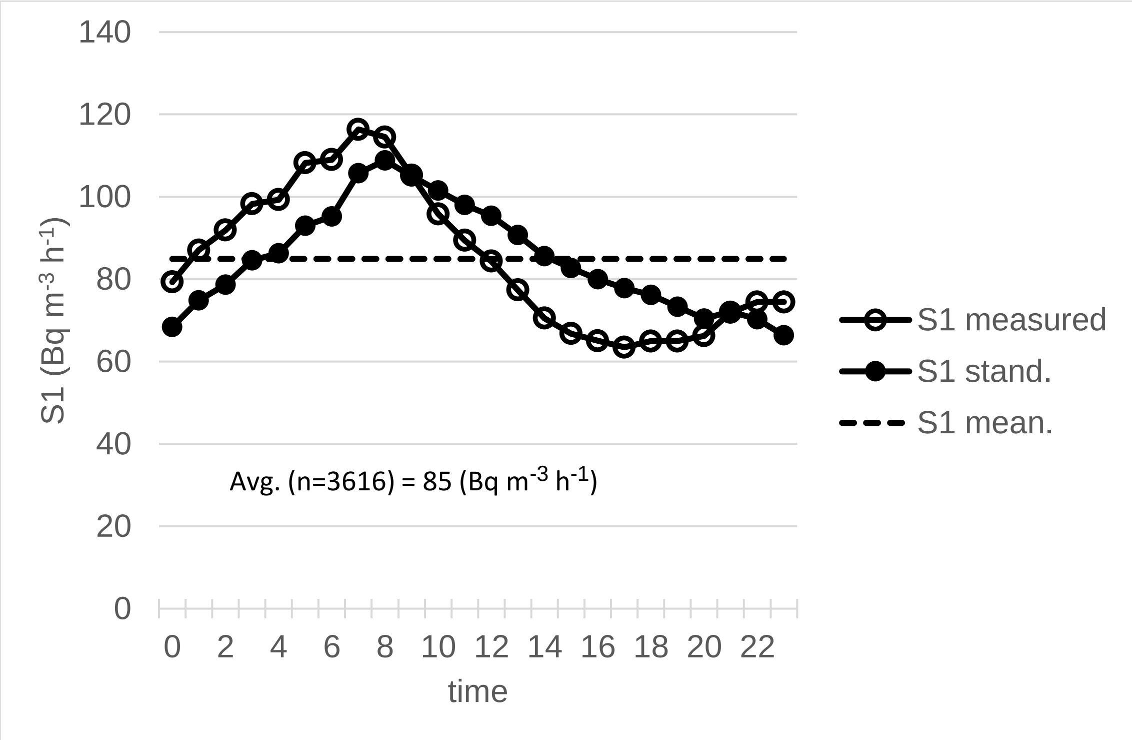


Figure 3. Dependence of measured rate of radon entry S throughout the day in the slab-on grade house A. S1 stand. = covariate corrected group average. Analysed by analysis of covariance (Keskikuru et al., 2001, **Publication II**).

5.1.4 Effect of barometric pressure and rain

Barometric pressure changes were examined in two houses with slab foundations, of which one (B) was one of the six houses built on a gravel esker, and the other (A) was a house built on the ground on fragmented rock (**Publication II**). The impact of change in air pressure on the change in radon entry rate was examined using linear regression analysis. The three-hourly measured averages at Helsinki Vantaa airport were used as the air pressure data. The fluctuations in barometric pressure (with a 3-hour measurement interval) during the measurement period at both sites was irregular. Statistical examination showed that the fluctuation in barometric pressure did not affect the radon source strength. Graphical analysis of the source strength and the barometric pressure change also supported the results of the previous analysis (Figure 4). (Figure 7 of **Publication II**). The average change in air pressure with a three-hour measurement interval was ±26 Pa h^{-1} and the radon entry rate change was ±5 Bq m^{-3} h^{-1}.

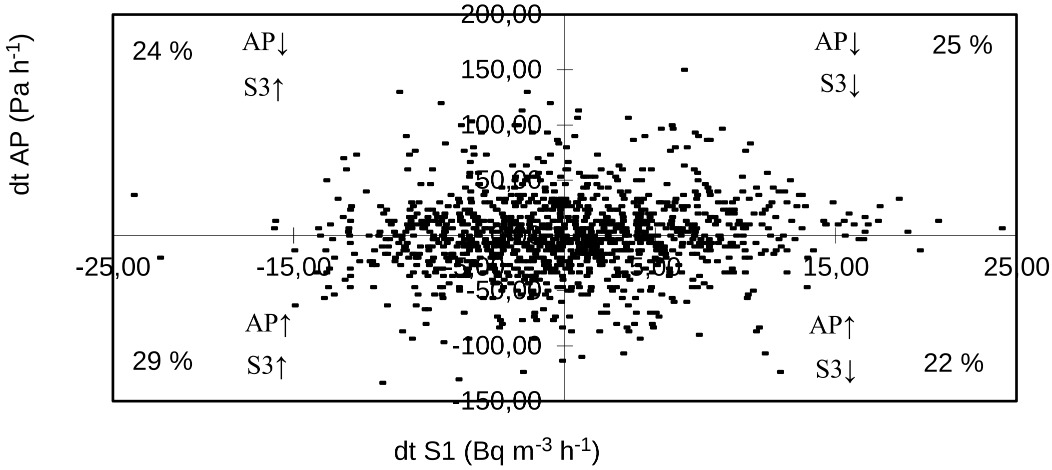


Figure 4. Dependence of measured rate of radon entry dt S (Bq m^{-3} h^{-1}) on changes in barometric pressure dt AP (Pa h^{-1}) in the slab-on-grade house A. n = 1195 with 3 h measurement interval (Keskikuru et al., 2001, **Publication II**).

The effect of rain was examined in house A during a period when the ground was not frozen. For the examination, the measurement data was grouped into four categories: no rain, before rain, rain, and after rain. The impact of rain on the radon entry rate was analysed using covariance analysis. The analysis was used to calculate the group averages of rainfall data and the covariate-corrected group average deviations from the total average. The results are shown in Figure 5 (Figure 7 of **Publication II**). The entry rate group average values were lower than the average, which is explained by the smaller temperature differences. In the statistical examination, the increase in radon entry rate after rain is small in relation to the size of the covariate correction and the coefficient of determination.

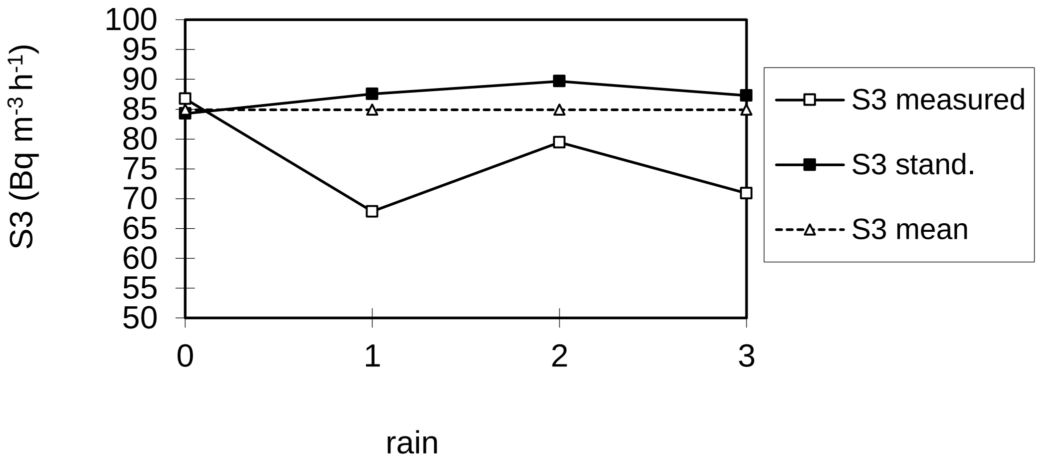


Figure 5. Dependence of measured rate of radon entry S (Bq m^{-3} h^{-1}) on rain in the slab-on-grade house A. Measurements: 0=no rain, 1=before rain, 2=after rain and 3=rain. Analysed by analysis of covariance (Keskikuru et al., 2001, **Publication II**).

5.1.5 Radon mitigation by ventilation

The long-term concentration of radon was measured in the same rooms as the short-term measurements. The long-term radon was determined by using alpha track detectors. The radon concentrations were measured during the coldest time of the year, from November to April. The old ventilation systems were removed from houses A-F and replaced with ventilation units suitable for controlling pressure differences (Publication IV). The ventilation systems were changed to meet the ventilation regulations at the time of installation and the operating instructions. After installation of the equipment, supply and exhaust airflows were measured for each room and were adjusted to comply with (D2), the design values. Ventilation was used 24 hours a day at all the houses.

According to the measurement results, continuous effective ventilation decreased the radon concentration at houses A to F by 17% to 69% of the initial situation in stages when the ventilation pressure difference periods were not operating (Table 11). In the initial situation at sites A, and C to F, there was mechanical supply and exhaust ventilation where the ventilation unit was combined with the oven extractor hood. House B only had mechanical exhaust ventilation.

During the measurement periods when the pressure difference control was operating, radon concentration decreased accordingly by 41% to 88% from the initial situation (Kokotti, 1995).

5.2 Pressure differences in supply and exhaust ventilated houses

The main findings of the pressure difference measurements are presented in **Publication IV**. The mechanical supply and exhaust air ventilation system at the research sites was regulated so that the supply airflow in the single-storey detached houses (A, C-F) was 15% lower than the total exhaust air flow, and in the two-storey house (B) it was 25% lower. Table 11 (Figure 1 of **Publication IV**) presents the measurement results for the periods when the pressure difference regulator was not being used. According to the measurement results, the living spaces in the six houses with supply air ventilation had, however, a slight overpressure with respect to the outdoors and the attic. Some of the supply air exited as leaks through the building envelope. The results of the total airflow measurements taken in the ducts during the measurement periods at each site differed from the control requirement for total air flows. The average of the attic-indoor pressure differences was 0.7 Pa when the supply and exhaust fans' pressure difference control was not used, and the corresponding figure was 1.4 Pa when the pressure difference control was used. When four comparable houses (A, B, D and E) are compared, the average value for the pressure difference between the indoor-outdoor was 0.3 Pa and the corresponding figure for the indoor and the attic was 0.7 Pa. The supply and exhaust ventilation (installed in accordance with the design instructions) at the houses on the research sites was able to maintain a small overpressure in the living areas equipped with supply air ventilation. According to the duct measurements at the research sites, the total airflows of the supply and exhaust ventilation system deviated from the set values (Table 11).

Table 11. The table gives mean values of hourly measurements of difference in indoor-outdoor pressure ($PD_{in\text{-}out}$), difference in indoor-attic space pressure ($PD_{in\text{-}attic\ space}$), difference in indoor-outdoor temperature ($T_{in\text{-}out}$), mechanical ventilation rate (λ_{bmw}), house total ventilation rate (λ_v), and wind speed (Ws). The number of measurements is given as the long-term (alpha track detector) concentration of indoor radon (Rn) and the airtightness ($n_{50\ Pa}$). The measurement time n (day) is also given (Keskikuru et al., 2000).

Factors	**Houses**						
	A	**B**	**C**	**D**	**E**	**F**	**G**
After mitigation, during period pressure control system off							
n (day)	67	29	8	26	14	13	27
$PD_{in\text{-}out}$ (Pa)	-0.0	-0.0	-	0.4	1.0	-	-
$PD_{in\text{-}attic\ space}$ (Pa)	0.1	0.8	0.5	0.8	0.7	1.3	-0.6
λ_{bmw} (h^{-1})su./ex. λ_v (h^{-1})	0.50/ 0.56	0.56/ 0.54	0.58/ 0.62	0.75/ 0.80	0.55/ 0.49 0.75 ± 0.2[a]	0.55/ 0.35 1.1 ± 0.2[a]	0.35/ -
$T_{in\text{-}out}$ (°C)	11.7	28.3	22.0	27.1	21.8	15.2	19.2
Ws (m s^{-1})	0.5	1.2	0.9	0.9	1.5	1.0	1.1
$n_{50\ Pa}$ (h^{-1})	8.6	3.6	5.8	6.0	3.6	3.1	3.1
Rn (Bq m^{-3})	280 (24h/d)	980 (24h/d)	630 (24h/d)	660 (24h/d)	520 (24h/d)	260 (24h/d)	-
Before mitigation, intensity ventilation							
Rn (Bq m^{-3})	Ex+Su+CA 630 (24h/d)	Ex 3080 (0h/d)	Ex+Su 795 (24h/d)	Ex+Su 870 (24h/d)	Ex+Su 630 (24h/d)	Ex+Su 845 (24h/d)	-
Initial condition, original ventilation							
Rn (Bq m^{-3})	Natural 850 (24h/7d)	Ex 2931 (0h/7d)	Ex+Su 2780 (1h/d)	Ex+Su 1520 (4h/d)	Ex+Su 1020 (18h/d)	Ex+Su - -	-
Remedial efficiency (%)[b]	55	68	21	24	17	69	-

[a] one week PFT-measurement at end of the period, [b] compared to before mitigation
Ex+Su = old combined exhaust and supply ventilation with kitchen fan, CA = circulation air, h/d = operating time per day

The houses examined are representative of the typical levels of airtightness at the time they were built, albeit that compared to today's standards these levels are poor. The airtightness figures ranged from 3.1 to 8.6 h^{-1}. The effect of deviations in regulation on the pressure differences is considerably less than in modern houses with an airtight envelope ($n_{50\ Pa}$<1 h^{-1}) (Figure 6).

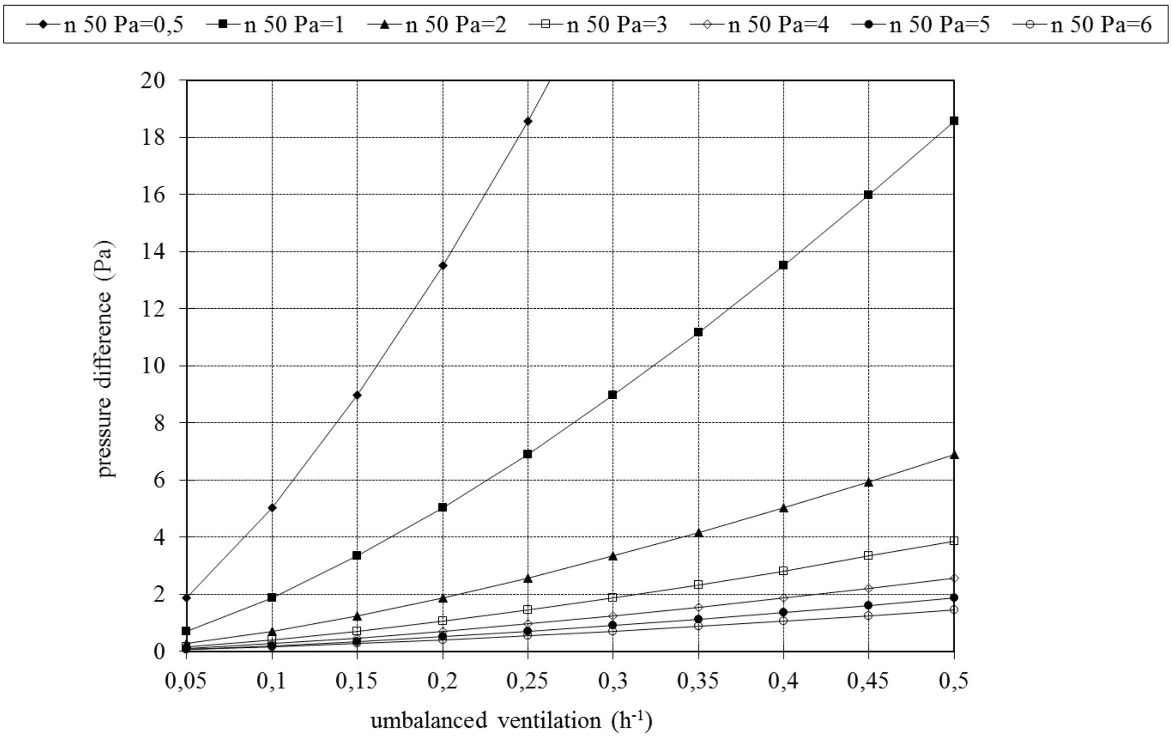


Figure 6. Dependence of difference in indoor-outdoor pressure (Pa) on air change rate of unbalanced ventilation (h^{-1}) with different values of the tightness ($n_{50\ Pa}$, h^{-1}) of the house. Approximated by $\Delta \mathrm{P(Pa)} = \left(\frac{\mathrm{Q_{umv}}}{\mathrm{n_{50\ Pa}}}\right)^{1/n}$ x 50, where n=0.70, flow exponent (-)

5.3 Indoor airflow and infiltration

In **Publication IV**, air change and transfer airflows between zones was studied in two detached houses (E and F) using the PFT method with two- and three-zone models. In addition, the supply and exhaust airflows were measured at the same time using a continuous measurement system. The measurements were scheduled to be done in May. The length of each measurement cycle, of which there were four, was approximately one week. According to the measurements, the houses worked on a two-zone principle. Table 12 shows the measurement results with the margins of error. The measurement results are from periods when the ventilation pressure control was not in operation. In the periods for which the pressure control was in operation, the results were quite similar.

Table 12. Indoor air flows in houses E and F.

House E			
From room	To room	Air flow rate, $m^3 h^{-1}$	Inaccuracy, $m^3 h^{-1}$
bedroom 1	other rooms	90	±20
other rooms	bedroom 1	70	±20
bedroom 1	bathroom	10	±5
bathroom	bedroom 1	1	±1
other rooms	bathroom	20	±10
bathroom	other rooms	10	±5
House F			
From room	To room	Air flow rate, $m^3 h^{-1}$	Inaccuracy, $m^3 h^{-1}$
bedroom 1	other rooms	140	±30
other rooms	bedroom 1	70	±20
bedroom 2	bathroom	10	±5
bathroom	bedroom 2	1	±1
other rooms	bathroom	40	±20
bathroom	other rooms	10	±5

zone 1=bedroom, zone 2=kitchen+living room, bedrooms and zone 3=bedroom

There was almost complete mixing of air between the living spaces fitted with supply air ventilation as the doors were open for most of the time. The relationship between the bedroom and living room two-directional transfer airflows fluctuated between 1.3 to 2. Bedroom supply air generated a greater transfer airflow from the bedroom into the living room than did the transfer air from the living room into the bedroom generated by the indoor airflows. Between the bathroom and the other living spaces, there was only a flow from the depressurised bathroom space to the other spaces when the door was opened. According to the PFT and air volume measurements, about 40 - 65% of the supply air in the depressurised bathrooms came as airflows from the living areas, while the remainder leaked in from outside.

5.4 Radon, fungal spores and MVOCs reduction in the crawl-space house

The reduction of radon, fungal spores and MVOCs in the crawl-space house is described in the **Publication V** case-study. This was a single-storey detached house which previously had exhaust ventilation for ventilating the crawl space because of both moisture and mould growth problems. The house and the crawl space were later equipped separately with new, more efficient supply and exhaust systems. The crawl space, which was previously pressurised by 3.7 Pa relative to indoors, was adjusted to maintain a negative pressure of 2.7 Pa relative to indoors. The negative pressure of the house decreased from 1.0 to 0.2 Pa relative to outdoors. The changes increased the radon concentration in the crawl-space air from 340 Bq m^{-3} to 755 Bq m^{-3}, but due to changed pressure conditions and decreased infiltration, the indoor concentration of radon (25 Bq m^{-3}) was not changed by the flow from the crawl space.

According to marker measurements, the overpressure in the crawl space generates a leakage flow (6 m^3 h^{-1}) back into the living areas. Sub-floor leakage accounted for about 8% of the total exhaust flows. The crawl space and room air radon concentration ratio (12.5) and the exhaust airflow and the leakage flow ratio (13.5) corresponded well with each other. Similarly, the ratio of the concentration of the prevailing microbe (*Aspergillus*) in the crawl space and in the house was 55, while a decline of 0.5 in the ratio for MVOC compounds was achieved.

No visible mould growth was detected on the lightweight concrete roof surface of the crawl space. However, the concentrations of mesophilic (61300 cfu g^{-1}) and xerophilic (83800 cfu g^{-1}) fungal spores in the material samples were quite high. The prevailing species in the material sample was *Aspergillus* (90% of the total content), which was also the dominant species in the crawl space and house air samples.

At the start of the first monitoring session after the change in ventilation, the over-pressured crawl space was regulated to be depressurised in relation to the indoor spaces and the living spaces were regulated to be slightly depressurised with respect to the outdoor air. At the beginning of the second, colder monitoring period, the crawl-space supply and exhaust air were, however, regulated again because the depressurisation of the house increased at the start of the period. In order to ensure the depressurisation of the crawl space, the amount of exhaust air had to be increased and the air change measured in the exhaust duct increased to 3.2 h^{-1}.

The humidity of the crawl space air did not decrease during the monitoring periods after the change to the ventilation because the moisture capacity of the crawl space was high and the removal of moisture from the wet sand layer foundation of the crawl space is slow. However, the emission speed of mesophilic fungal spores fell by 89% and the corresponding figure for xerophilic fungal spores was 84%. Before the changes to the ventilation, the dominant species in the crawl space and house air was *Aspergillus*. After the changes to the ventilation, the predominant species in the indoor air of the house were *Cladosporium* and *Penicillium*. The corresponding dominant species in the crawl space were *Penicillium* and *Aspergillus*. This may indicate that the crawl space microbes were no longer a significant source of infection for the indoor air after the repairs.

The concentrations of VOC and carbonyl compounds in the crawl space, which are possibly produced by microbes, decreased because of the increased ventilation. 3-methyl-2-butanol, 3-methyl-1-butanol, 1-pentanol and 1-heksanol were found in the crawl space air, and these are most probably the products of microbial metabolic processes.

5.5 Crawl space Modelling

In **Publication V**, computational modelling was used to examine the effect of the airtightness of depressurised open and closed crawl spaces, and the air change and various airtight structures and construction materials on the crawl space temperature and humidity conditions. A more detailed description of this study`s heat, air and moisture transport modelling is presented by Salo et al., 2018. The crawl space conditions were examined over a period of two years in outdoor air conditions that were critical for mould growth. The simulation results were time-dependent temperature and relative humidity values, based on which, using the Finnish mould growth model, mould growth index values were calculated that describe the risk of mould growth using the mould growth sensitivity classes 1 (very sensitive) and "SC 3" mould growth sensitivity class 3 (medium resistant). The parameter for the calculation was a pressure of -10 Pa in the crawl space compared to the living space, which was achieved with exhaust air ventilation.

In the case of an open foundation structure with a gravel fill, the convective airflow via the ground depends on the permeability of the gravel. A more permeable gravel ($1x10^{-8}$ (m^2) allows the convective air flow via the ground caused by depressurisation to be about 0.028 m^3 s^{-1}, while the figure is only 0.003 m^3 s^{-1} with less permeable gravel ($1x10^{-9}$ (m^2). Also, gravel materials that are coarser than $1x10^{-8}$ (m^2) are often used in foundations. When permeability is $1x10^{-7}$ (m^2), the convective airflow via the ground increases to a value of 0.28 m^3 s^{-1}. The simulation assumes that the crawl space plinth and sub-floor structures are airtight.

The open foundation air-change rate is greater because the airflow caused by depressurisation in an open ground structure allows convective airflow via the ground. The simulation also examined the changed convection air conditions in the airflow path in the gravel fill. According to the simulation results, the outdoor airflow caused by the crawl space depressurisation (-10 Pa) dries up significantly as it travels via the soil into the crawl space. This phenomenon depends on the characteristics of the gravel and air flow and requires further research.

The Mould index for open ground structures increases at an earlier point in time at all air change rate values than does the Mould index for outdoor air. The temperature of the crawl space is lower than that of outdoors, which means that outdoor air introduced to the crawl space cools, causing the relative humidity to rise, and thus a higher Mould index. The Mould index is not dependent on the permeability values used in the calculation, and is only slightly dependent on the air change rate in the crawl space, whose change is not directly related to the change in the Mould index. When the mould growth sensitivity class (SC3) for building materials is 3 (concrete etc.) the structure is effective because the Mould index remains under 1, and no mould growth is observed. On the other hand, this structure is not recommended when the mould growth sensitivity class (SC1) of building materials is 1 (pine sapwood), because the Mould index rises over the permitted value of 1.

In the other structures, the bottom of the crawl space was airtight, which prevents convective air flow caused by pressurisation via the ground. For the simulation, the ground structure used was alternatively concrete, concrete+insulation, and insulation and a plastic sheet. The Mould index was less than 1 in all the simulations in which air-sealed structures were used and the mould growth sensitivity class of building materials was 3. An increase in the Mould index over time was only observed when the air change rate was 0.2 - 1.0 h^{-1} in the plastic-covered ground structures, and the plastic insulated ground structure gave higher values than an XPS insulated ground structure. The Mould index of plastic- or insulation-covered ground structures decreases as the air change rate increases. When the mould growth sensitivity class of building materials in the crawl space is 1 (pine sapwood) with a concrete surfaced foundation structure, the Mould index remained under 1 up to an air change rate of 0.6 h^{-1}. The Mould index rises to over 1 with higher air change rates. The Mould index for a ground structure built with concrete and XPS insulation with a mould growth sensitivity class of 1 remained under 1 up to an air change rate of 2 h^{-1}. When air change rates were higher than this, the Mould index exceeded 1.

When comparing the relative humidity of a crawl space insulated with concrete or plastic, at an air change rate of 0.6 h^{-1}, it was found that concrete insulation had a lower relative humidity during periods when the outdoor air humidity was high, than with plastic insulation, in addition to which the fluctuation is less. The Mould index exceeded 1 with all air change rates when ground structures were made with insulation or plastic and the mould growth sensitivity class of building materials was 1, and the Mould indexes form the same way as for open gravel-filled ground structures.

6 Discussion

6.1 The effect of different factors on indoor radon

The impact and dependence of physical and meteorological factors on the radon entry rate in seven houses was examined using linear regression analysis. The coefficient of determination of the measured factors was not very high because radon levels and movement in the soil are affected by several different factors. The radon concentration of soil air is the most important factor that increases the radon concentration indoors. Many physical factors, such as the soil properties and moisture affect the generation of radon and its movement in the soil. The movement of soil gas containing radon is affected by other dynamic soil factors, such as its permeability. The final factor affecting the movement of radon into the house is the airtightness of the building's foundation structures. The physical properties of the building, the indoor-outdoor air temperature difference and unbalanced ventilation affect the pressure difference between the building's indoor air and the soil. As for physical processes in the soil, outdoor air factors such as wind and wind direction, outdoor temperature and rain affect the generation of radon in the soil and its movement and accumulation. The wind also flushes out radon in the soil and increases the ventilation of the building. The effects of different physical factors can be immediate (wind, temperature difference, etc.) or slow, such as the seasonal variations in soil moisture and temperature.

In the correlation analysis between pairs of variables at each site, the radon entry rate correlated strongly with the indoor-outdoor temperature difference and with the indoor-outdoor pressure difference. This result accords with other studies (Xie D et al., 2017; Porstendorfer et al., 1994; Nazaroff et al., 1988; Rowe et al., 2002). These researchers all reported that indoor radon concentrations rose with increasing indoor-outdoor temperature differences. In this study the coefficient of determination, however, was not very high. The maximum coefficient of determination was observed at site A, where a house built on a gravel fill is located on rocky ground. According to physical models, the indoor-outdoor temperature difference affects the indoor-outdoor pressure difference, and this is an explanatory factor for the inflows of radon and the indoor radon concentrations. However, in the research the most important explanatory factor proved to be the temperature difference. In previous radon studies, it is generally assumed that the pressure below the building’s slab is the same as the outside pressure. However, the measured indoor-outdoor pressure difference possibly does not exactly match the pressure difference between indoors and the soil under the slab, as the wind has a greater effect on the measurement of the indoor-outdoor pressure difference.

In this study, the air pressure difference measured between the indoors and the attic balances the windward and leeward side pressure and gives a more realistic measurement result than the pressure difference measured from one measurement point on the outer wall. In the pressure difference calculation models, the effect of the wind is taken into account as the average of the windward and leeward sides. The indoor-outdoor pressure difference can be measured as an average from the windward side and below the windward side, or from a ventilated attic that acts as a balance against the wind, but this does not give a true picture of the pressure difference above the internal slab, which is the only important factor for the convective flow from the soil caused by pressure difference. Previous radon studies where the pressure difference was measured above the slab, or those which compared measurement results to the measured pressure difference above the envelope have not been found in the literature.

The radon entry rate value S was calculated using the supply air flow as the air volume variable. The air change calculated from the supply air volume better describes the air change in spaces fitted with supply air ventilation than using the amount of exhaust air. The indoor radon concentration was measured in living areas equipped with supply air ventilation and these areas were assumed to be a perfectly mixed single zone. The numerical value of the source strength is relative because the source strength was calculated from the total supply-air flow. On the other hand, the room-specific supply-air flow does not include other transfer air flow from other spaces. In this case, the indoor radon concentration was measured for living areas through which most of the supply air from other spaces flows as transfer-air flow to spaces with exhaust air ventilation. In this case, the assumption was also made that the supply air correlated better with radon concentration in a space fitted with supply air ventilation that the exhaust air would. A significant proportion of the infiltration air in spaces with exhaust air ventilation would possibly flow outdoors as leakage.

6.1.1 Effect of wind on indoor radon

According to this study (**Publication III**), the wind speed and wind direction affected the radon entry rate in all houses. In the case of a house built on an impermeable slope, the wind had no significant effect on air movement through the top soil. On the other hand, wind might also induce the transport of radon from an unventilated room to a ventilated living space. The indoor transport of radon could be prevented by using ventilation in all rooms and by tightened structures. In the case of the houses built on the permeable esker, wind from certain directions increased radon entry with increasing pressure difference across the structure and with an increasing concentration of radon in the soil pores. A more detailed examination of the radon entry rate would require continuous measurement of the pressure difference between the indoor air and the foundation slab and of the soil radon concentration in the immediate vicinity of the building and below the building's slab. Wind blowing perpendicularly to the esker increases the radon concentration in the soil gas below the slab. Soil gas flows through the gravel layer and its concentration are increased during the flow. Wind from other directions away from the esker does not increase the concentration of the soil air flow in the same way, and the airflow can flush out the gravel layer below the building, depending on the wind direction.

The best correlations of indoor radon concentration and the coefficient of determination were found when the wind direction was perpendicular to the esker. The flushing effect of the wind has been demonstrated previously by calculation. According to Riley's (Riley W.J., et al., 1996) calculations, the wind reduces radon levels in room air because the pressure field in the vicinity of the building caused by the wind dilutes the radon concentration in soil gas and at the same time increases the rate of air change in the building. The dilution effect of the wind is greatest on the edges of the building on the windward side. Arvela et al. (1994) found in their research that in the winter, wind blowing against the esker increased the radon concentration in the upper part of the esker, but in the warmer summer period even a strong wind was not able to reduce the flow of soil gas and the radon concentration.

6.1.2 Effect of barometric pressure and rain

Changes in barometric pressure were examined in two houses with slab foundations **(Publication II)**. The effect of barometric pressure has previously been examined in several studies with conflicting results. Calculations have shown that fluctuations in barometric pressure can increase radon concentrations in indoor air. Experimental measurements have been done in targeted country studies where fluctuations in barometric pressure are semi-diurnal. Semi-diurnal variations in barometric pressure are the result of atmospheric tides resulting from solar heating and Coriolis forces on the Earth.

According to regression analysis, at site A the change in atmospheric pressure was not a significant explanatory factor. Only 27% of the fluctuation in radon entry rate was explained by fluctuations in the atmospheric pressure. Similarly, in the regression analysis for house B, after the change in indoor-outdoor pressure difference, the most important explanatory factors for the change in radon entry rate proved to be the change in temperature difference and the change in barometric pressure. The value of the regression coefficient for change in air pressure was -0.033 (p=0.024), i.e. according to the analysis, a reduction in atmospheric pressure would increase the radon entry rate. Other variables in the model were not significant explanatory factors. Indeed, only 13 % of the fluctuation in radon entry rate was explained by fluctuations in other explanatory factors. This issue of the effect of air pressure change may also be affected by the residual variation. The small coefficient of determination at both houses was affected by too few weather observation measurement intervals. The measurement interval variables should have been considerably shorter than the three-hourly interval used for the Finnish Meteorological Institute weather observations, so the examination could have been done using several different air pressure change frequencies. The significance of fluctuations in atmospheric pressure on radon source strength cannot be very large, since the diurnal air pressure fluctuation at both sites was irregular. In Hintenlang's study, the source strength increased when the air pressure fluctuation interval was 12 hours (Hintenlang and Al-Ahmady, 1992). Results supporting the previous analysis were also obtained in the graphical examination of the change the source strength and change in barometric pressure, where the change in air pressure was not observed to influence the change in radon entry rate.

Soil moisture has been shown to affect the generation and movement of soil gas containing radon in several stages. (Nazaroff et al., 1985; Arvela et al., 2015; Breitner et al., 2010). In his research, Nazaroff observed heightened radon levels after heavy rain. Because of rain, the permeability at the soil's surface falls compared to the dry soil beneath the slab. According to the results of the study obtained using Arvela's multi-disciplinary analysis, the measured radon concentrations in autumn and spring were higher than expected and this can also be explained by the seasonal variation in soil moisture.

The direct effect of rain on radon source strength was examined at study site A using covariance analysis. The effect of rain was taken into account after the soil had thawed. The results of this analysis did not clearly show that rain influenced the short-term variation of radon entry rate at site A. The group averages for the radon entry rate values before rain, during rain and after rain were smaller than the averages which were explained by small temperature differences. The covariate corrected values after rain for radon entry rate were slighter higher (about 5%) than the average for all the material. The increase in radon entry rate after rain is low in relation to the size of the covariate correction and the coefficient of determination. The study did not consider the actual saturation at different soil depths, which changes more slowly, and therefore the effect of soil moisture on the diurnal fluctuation in soil and room air radon levels cannot be deduced from the results. Such research would require a more extensive study design, but our results indicate that the short-term variation in radon source strength due to rain is negligible. Research into the effects of rain and soil would require simultaneous, long-term measurements of indoor radon concentrations, soil moisture content and radon concentrations in the immediate vicinity of the building and from under the foundations of the building.

6.1.3 Radon mitigation by ventilation

Ventilation reduced radon concentrations effectively in all the studied houses. It is difficult to achieve low enough concentrations by increasing ventilation when radon concentrations are high in houses, so ventilation has to be used in combination with other methods. The results show that it is difficult to predict the effects of repairs to the ventilation system (**Publication IV**). However, the best results were obtained in buildings where ventilation had previously been ineffective, or depressurisation had been high before measures were taken to improve the ventilation. Well-adjusted ventilation at sufficient power was used continuously in all the research houses. Ventilation control also affects a building's pressure difference. The reduction in radon concentration achieved using ventilation repair measures was good when the initial situation in the five houses was mechanical supply and exhaust ventilation and in the one with mechanical exhaust ventilation. These results are similar to previous studies. The reduction in radon concentrations for detached houses (167 houses) was 20% to 80% when mechanical supply and exhaust ventilation was installed (Hoving et al., 1993). It has been observed that well-regulated supply and exhaust ventilation has reduced radon concentrations by 50% to 80% (Keskinen et al., 1989; Hoving et al., 1993; Kokotti et al., 1994; Kokotti, 1995). According to the study of the Radiation and Nuclear Safety Authority, typical reduction factors are 10 – 40%. The reduction factors exceed 50% only in rare cases when the initial air exchange had been low or the underpressure level had been high. The results of the efficiency of various mitigation methods are based on a questionnaire study in 400 Finnish dwellings and on-site studies in numerous houses. Mitigation work based on ventilation aims at increasing the air exchange or reducing the underpressure, or both (Arvela et al., 2008).

Regulation of pressure differences did result in further reductions in radon concentrations, but these were not particularly significant. This resulted from the pressure difference at the houses. The functioning supply and exhaust ventilation system installed in a detached house in accordance with the current design guidelines. This naturally maintains a small overpressure in living spaces fitted with supply air ventilation irrespective of the pressure difference regulation. Nowadays it has become common to install exhaust vents in living spaces too, so that living spaces are more depressurised.

6.2 Pressure differences and indoor air flow and infiltration in supply and exhaust ventilated houses

The physical models of ventilation described in paragraph 2.5 of the literature section are single-zone models, which require the building being studied to have an open, single-zone space. In a building with an airtight external envelope and adequate transfer air routes and mechanical exhaust ventilation, the single-zone model can be used. In more accurate examinations of the pressure difference and air change for each room, a multi-zone model based on the mass flow balance equation is used, as this takes into account all the transfer routes between the outdoor and indoor spaces.

In Publication IV, air change and transfer airflows between zones were studied in two detached houses (E and F) using the PFT method with two- and three-zone models.

According to the measurements, the houses worked on a one-zone principle. There was almost complete mixing of the air between living spaces fitted with supply air ventilation as the doors were open for most of the time. The relationship between the bedroom and living room two-directional transfer airflows fluctuated between 1.3 to 2. Bedroom supply air generated a greater transfer airflow from the bedroom into the living room, than the transfer air from the living room into the bedroom generated by the indoor airflows. Between the bathroom space and other spaces, there was only a flow from the depressurised bathroom space to the other spaces when the door was opened. According to the PFT and air volume measurements, about 40 - 65% of the supply air in the depressurised bathrooms came as airflow from the living areas and the remainder through leaks from outside. The results showed that a ventilation system only functions as designed in houses that are sufficiently airtight.

Calculation of the transfer airflows between the zones led to high standard deviations. However, when the transfer airflows were of the correct magnitude, the results of the interpretable and repeated measurements did not differ significantly.

The ventilation was adjusted so that there was a slight depressurisation in the buildings in order to avoid condensation damage in the structures. In a mechanical supply and exhaust ventilation system, this is achieved by setting total supply air flow in single-storey detached houses to 20% (15%) and in two-storey houses to 25% lower than total exhaust airflow. The living spaces of the six houses in the study had a slight overpressure and some of the supply air was lost to leaks through the living areas' building envelope. The average of the attic-indoor pressure differences was 0.7 Pa when the pressure difference control was not used, and the corresponding figure was 1.4 Pa when the pressure difference control was used.

Well-functioning supply and exhaust ventilation at the houses, installed in accordance with the design instructions, was able to maintain a small overpressure in living areas equipped with supply air ventilation. The pressure difference in different spaces is affected by the supply and exhaust ventilation balance, the dimensioning of transfer routes, and leaks from the building envelope. The building's pressure differences depend on the airtightness of the building and the difference in the total air volumes. The gap in the door used as a transfer route between the WC or bathroom and living spaces has a pressure difference of about 2 Pa, when the transfer airflow is so designed. Spaces with supply air ventilation have a slight overpressure produced by the difference in supply and exhaust air volumes in accordance with the guidelines. The pressure differences generated in the building depend on the airtightness of the building and the difference in the total volumes of supply and exhaust air. The sites studied represent the acceptable airtightness standards for the time they were built, although this is poor by today's standards. The effect of deviations in the regulation of pressure differences is considerably less than in it is with modern general levels of airtightness ($n_{50\,Pa}$<1 h^{-1}).

Pressure differences can be affected by the location principles for ventilation air-terminal units. Nowadays it has become common to install exhaust vents in living spaces, which makes them more depressurised. When installed like this, there is no need to design gaps under the doors to bedrooms. On the other hand, in our research, the slight overpressure did not seem to cause humidity damage. The ventilation solution in question is very common in detached houses from the '80s and '90s. Another significant observation is that the terminal equipment's ventilation volumes in today's airtight buildings should initially be set to the design air volumes. The building's pressure differences should avoid pressure rising above the guidelines to prevent moisture damage to the ceiling, windows and upper parts of the walls. Afterwards, the final regulation of the pressure difference between living spaces equipped with supply air ventilation and the outdoors to the guideline pressure difference must be done at the same time by adjusting the pressure difference measurement and the total air volumes. The adjustment should be made at different ventilation powers during windless outdoor conditions. As well as the weather conditions, the building's pressure differences are affected by the stability of the ventilation unit's total air volumes. Clogging of the ventilation's filters and measures to prevent frost in the heat recovery cell affect the air volumes passing through the ventilation unit. Clogging caused through using supply and exhaust air filters in a ventilation unit intended for residential buildings is caused by under-dimensioned filters and poor maintenance. The time at which supply and exhaust air filters clog up differ from one another, which causes a difference in the amounts of supply and exhaust air circulating when the ventilation is being used. The problem could be reduced by improving the product development of the ventilation equipment. In the largest ventilation unit, pressure regulation of the supply and exhaust air channels is a common solution for reducing the changes in air flows, and this technology could also be applied in ventilation units for residential buildings. Frost protection of the heat recovery cell, de-icing of the cell in winter and by-passing the cell during the summer affects the amounts of supply and exhaust air passing through the ventilation unit. Technical solutions could be used to keep an airtight house's air volumes and pressure differences within the set values during continuous operation.

6.2.1 Applicability of pressure-difference controlled mechanical ventilation

Pressure control limited the range of fluctuation in the pressure controller's air volume. Sliding values were used to define the limits within which the pressure control changed the flow through the supply and exhaust fan at different ventilation powers. The solution prevented airflow controls being set at their full positions and ensured a sufficient exhaust air flow.

In the houses in our studies, the pressure difference was controlled without any technical faults in the mechanical ventilation of the houses. Attention must be paid to the accuracy of the pressure difference measurement sensors, their susceptibility to interference and their longevity. The usability of the system was restricted by the poor airtightness of the buildings with the result that regulation of the pressure difference through relatively large changes in the volume of air did not have a significant effect on the pressure difference. It was observed in this study (**Publications I-IV**), that in the living spaces of a building with ventilation that has been implemented in accordance with the guidelines, there is a slight overpressure or depressurisation which reduces the need to control pressure difference. This research confirmed findings that the function of mechanical ventilation is most effective in airtight houses. Measuring the pressure difference as a control feature is made from an outside measurement point on one façade, or in the attic. It is difficult to achieve functional control using pressure difference measurements, because the measurement does not give an accurate picture of the real pressure difference. Wind speed and direction have a strong effect on the measurement result. Measuring the pressure difference from one point on the building envelope where there is a prevailing wind does not give an accurate picture of the real pressure difference between the building and the sub-floor. The pressure on the envelope caused by the wind depends on the wind direction. The effect of the wind and the wind direction cannot be determined from one measurement point located on a façade. A ventilated attic works passably well as a pressure balancer for variable wind and wind direction. This has also earlier been shown experimentally by a few researchers (Korkala and Siitonen, 1986; Karvonen and Virtanen, 1988). However, not enough research has been carried out into the usability of an attic as an outdoor measurement point. Similarly, in theoretical studies of a buildings' pressure differences, it is assumed that the pressure difference between the indoor air and the soil is the same as the indoor-outdoor pressure difference. With reduced structural leaks in the sub-floor, measurement of the pressure difference could be taken across the sub-floor slab and in that case the measurement would better correspond to the sub-floor leakage behaviour so that the fluctuation in pressure difference caused by the wind would be mitigated.

6.3 Radon, fungal spores and MVOCs reduction in the crawl-space house

In order to maintain the quality of indoor air, the microbiological growth conditions in the crawl space must be limited in order to minimize microbe growth on the crawl space's surfaces and structures. Besides avoiding the use of building materials that contain organic materials, microbe growth conditions in the Nordic climate can be limited by controlling the temperature and, especially, the humidity of the crawl spaces. Nevertheless, it is impossible to build a completely microbe-free crawl space. The conditions in a crawl space are not the same as the conditions indoors, and harmful substances such as radon and microbial metabolic end-products are also released from the soil. The introduction of harmful substances such as microbes, MVOCs and radon via air leaks from the crawl space to the indoors can be prevented with an air-sealed sub-floor structure and depressurisation of the crawl space.

One case study involved measuring the microbiological, radon and VOC conditions in the crawl space and living spaces of a detached house before and after ventilation changes **(Publication V).** The case study provided information on the impact that ventilation solutions have on the microbiological conditions of crawl spaces and living spaces and the introduction of radon into them. The spaces examined were a crawl space pressurised with exhaust air, and a crawl space and living spaces equipped with separate, mechanically balanced and reconditioned supply and exhaust air. The effects of depressurisation of the crawl space on the microbial conditions were also examined by increasing the crawl space's exhaust ventilation.

According to this case study, the crawl space pressurisation system with exhaust air from indoors was successful in preventing the convective flow of radon from the soil, but increased microbial concentrations were detected in the crawl space because the warm moist air blown into it produced favourable conditions for microbial growth. Thus, this kind of crawl space pressurisation is, with certain qualifications, effective in controlling indoor radon levels if the slab is totally airtight and there are no organic materials in the filling soil or in the crawl-space structures.

The new supply and exhaust ventilation was adjusted so that the ventilation maintained a slight underpressure relative to the outdoors, and the new crawl space ventilation was adjusted so that the space was slightly depressurized relative to indoors. Carefully balanced separate two-way ventilation in the crawl-space, supply and exhaust ventilation in the living space, and also an airtight slab between them, appeared to be effective in preventing air infiltrating into the living areas from the crawl space. However, the air change rate of the crawl space (which was maintained underpressure relative to indoors) was high in both winter and summer conditions. After changes to the ventilation, the concentration of fungal spores and MVOC decreased after a short adjustment period. The concentration of MVOC of specific microbial species was very low in the crawl space, which in turn was lower than in the living space in spite of the fact that there was a higher concentration of fungal spores in the crawl space than indoors. However, the concentrations of MVOC of specific microbial species decreased as the concentration of fungal spores decreased. These findings are consistent with previous findings that microbial contaminated areas might not be verifiable with MVOC measurements.

A microbiologically safe crawl space was determined with a hygrothermal simulation utilizing the Finnish mould growth model. **(Publication V)**. The simulation allowed the temperature and humidity conditions to be studied (Salo et al. 2018), as well as mould sensitivity in open and closed ground structure crawl spaces over a period of two years. The Finnish mould growth model, which was specifically designed for this purpose, was used in the assessment of mould growth on different building materials. As a new approach, we used depressurisation (-10 Pa) of the crawl space in our calculation of the conditions for the mould model. The depressurization is aimed at continuously preventing harmful air leaks from the crawl space to the living space. Different structural options were used to specify the exhaust ventilation rate of the crawl space. These can be used to maintain a sufficient pressure difference and thus also prevent air leakage from the crawl space to the living space. The simulation allowed the design of the most effective microbiological conditions for a crawl space using various structural options.

The open uncovered ground (gravel) base in the crawl space of the first structure, which is typical in Nordic countries, was air-permeable gravel. Inspections were carried out with two typical gravel permeability values ($1x10^{-8}$ (m^2) and $1x10^{-9}$ (m^2)). In the second structure, the ground in the crawl space was covered with alternative solutions (concrete, concrete+XPS, XPS, plastic vapour barrier), which were assumed to prevent convective air flow via the ground and thus decrease evaporation in humid air.

Compared to previous crawl space studies, new data was acquired on functional ground structures in crawl spaces and on recommended air change rates. This data can be utilised in practice.

When the simulation assumed that the foundation wall was airtight and the soil's permeability value was $1x10^{-9}$ (m^2) and $1x10^{-8}$ (m^2), a crawl space with an open base of uncovered ground (gravel) could be kept depressurised with only moderate exhaust air ventilation. The infiltration of air into the crawl space through the soil is ten times greater than the permeability $1x10^{-8}$ (m^2) as the permeability $1x10^{-9}$ (m^2). Air coming through the fresh-air valves can be regulated. The amount of air coming through the soil is dependent on the permeability of the soil, and in the simulation the crawl space depressurisation was kept as a constant (-10 Pa). The effect of the outdoor airflow coming through the air vent on conditions in the crawl space reduced as the air flow coming through the soil increased.

The simulation assumed that the foundation was airtight. However, when permeability grows, the air change rate must be increased to achieve depressurisation, and air flow grows too strong in winter, cooling both structures and building technology devices in the crawl space. Managed air change in the crawl space is best achieved with airtight foundation structures in the crawl space.

No mould growth was simulated in the examined structures with different air change rate values for building material mould growth sensitivity class 3 (medium resistant; concrete, etc.). Open base uncovered ground (gravel) is only an effective solution in a crawl space, where there are no organic materials. In comparing calculations of the mould sensitivity class of building material (SC1) with gravel permeabilities of both $1x10^{-8}$ (m^2) and $1x10^{-}$

^{9} (m^2), there were no significant differences in the calculated results for the Mould index. However, in the more resistant class of materials (SC3) with gravel permeability of $1x10^{-9}$ (m^2) the values for the Mould index fluctuated more and were greater than they were with gravel permeability of $1x10^{-8}$ (m^2). Gravel permeability of $1x10^{-8}$ (m^2) can thus be regarded as an effective choice for covering the floor of an open base structure. Differences in the crawl space Mould index between the two gravel-permeability values affect the humidity and temperature conditions in the crawl space. The amount of moisture passing into the crawl space depends on the ratio of the amount of soil air and fresh vent air and the flow speed of the air flowing through the soil. It is possible that the lower Mould index values for the more permeable gravel were affected by faster airflow speeds, which allow less moisture to be fixed in the soil. The phenomenon depends on the characteristics of the gravel and the air flow and would require more research.

When the mould growth sensitivity class is 1 (very sensitive: pine wood, etc.) as it is for an air-sealed base of covered ground, the recommended ground structure is concrete + insulation with an air change rate of 0.2 to 1 h^{-1} for the exhaust air. A concrete ground structure with an air change rate of 0.2 to 0.6 h^{-1} is also very effective. Concrete structures have a good Mould index due to concrete's moisture capacity, but the Mould index rises if the air change rate is above the recommended level. The acceptable Mould index of concrete structures is due to concrete's sensitivity to moisture; it absorbs excess moisture and balances out changes in humidity. The heat capacity of the concrete slab also balances the temperature conditions in the crawl space. However, based on the examined cases, it is not possible to determine how much the heat capacity of the concrete slab affects the crawl space conditions and the Mould index in terms of the concrete slab’s moisture capacity. New data has shown that XPS insulation and plastic vapour barrier-covered ground are not to be recommended due to their high Mould index. For a crawl space with an air-sealed ground structure, the simulation assumed that the perimeter gap between the footer and the ground cover was airtight.

The computational simulation results were based on a multicomponent hygrothermal model used to analyze time-dependent temperature and humidity conditions in the crawl space. The results are quite consistent with the conclusions of earlier studies of crawl space done by Airaksinen and Kurnitski (Airaksinen, 2003; Kurnitski, 2000) who modelled conditions in non-depressurized ventilated crawl spaces. The effect of depressurization on subsurface water vapor transport and crawl space conditions has also been studied by Salo et al. (2018). The validity of Salo et al`s numerical model and reliability of the conclusions are difficult to evaluate without long term experimental data. More detailed content concerning the validity and reliability of this study`s heat, air and moisture transport modelling are presented by Salo et al., 2018. The practical application of the results should take into account the ideal theoretical calculation model features, which are not fully implemented in practice. For example, the stability of pressure differences, the air volumes and other conditions that affect leaks in the crawl space structures differ from the calculation model. The simulation used two consecutive test years that were critical with respect to the technical impacts of moisture (Jokioinen 2004). The outdoor air conditions differ from the conditions used in the study and so the real risks of mould growth may differ from the modelled results. In addition, the materials' surface temperature and the humidity conditions do not exactly match the crawl space temperature and humidity conditions. A microbiologically safe crawl space can be constructed taking the model's results into consideration. In addition to this, the depressurisation of the crawl space produced by exhaust ventilation prevents harmful air flows from the crawl space into the indoor air.

7 Conclusions

The effect of the measured environmental factors on indoor radon concentrations

The impact and dependence of physical and meteorological factors on the radon entry rate in seven houses was examined using linear regression analysis. In the correlation analysis between pairs of variables at each site, the strength of the radon source correlated strongly with the indoor-outdoor temperature difference and with the indoor-outdoor pressure difference. This result is similar to those of earlier studies. However, the coefficient of determination of the measured factors was not very high because radon concentration and flow in the soil is affected by several different factors.

The wind speed and wind direction affected the radon entry rate in all houses. In the case of the houses that were built on permeable esker, wind blowing perpendicularly across the esker increased the radon entry, whereas wind in the same direction as the esker's ridge did not have the same effect. The best correlations of indoor radon concentration and the coefficient of determination were found when the wind direction was along the same axis as the esker.

Change in barometric pressure was examined in two houses with slab foundations. According to the regression analysis, the change in atmospheric pressure was not a significant explanatory factor. The effect of fluctuations in atmospheric pressure on radon source strength cannot be significant, since measurements showed that the diurnal air pressure fluctuation was irregular. This result contradicts earlier studies in other countries **(**Nazaroff et al., 1985 and 1988; Hintenlang and Al-Ahmady, 1992; Robinson et al., 1997**)** where the fluctuation in barometric pressure was found to be a semi-diurnal, had relatively low-frequency air pressure change and which increased indoor radon concentrations.

The direct effect of rain on radon source strength was examined at two study sites using covariance analysis. According to the results, rain does not immediately influence short-term variations in the radon entry rate into the houses. Nevertheless, earlier studies (Nazaroff et al., 1988; Breitner et al., 2010; Arvela et al. 2015) have shown that soil moisture increases seasonal radon concentrations in soil.

Capability of mechanical supply and exhaust ventilation to reduce indoor radon concentration

Ventilation reduced the radon concentration effectively in all the studied houses and these results are similar to previous studies. However, it is difficult to reduce high radon concentrations in residential buildings to a sufficiently low level merely by increasing ventilation. In addition, the effectiveness of the reduction in radon levels varied from house to house.

The factors affecting the pressure differences and the internal airflows in houses

By adjusting the mechanical ventilation and thus, indoor-outdoor pressure difference, the radon concentrations decreased further, but it was no longer significant due to the existing pressure differences in the houses when the pressure difference was not controlled. The average pressure difference between the attic and indoor air was 0.7 Pa when the pressure difference was not controlled, and the corresponding value was 1.4 Pa when the pressure difference was adjusted. The supply and exhaust ventilation systems in the houses operated in accordance with the design instructions at their time of manufacture, and produced a slight overpressure in the living spaces where supply air vents existed. Pressure difference was controlled as long as there were no technical faults in the mechanical ventilation in the studied houses. The usability of the system was restricted by the poor airtightness of the buildings. Relatively large differences in the volumes of supply and exhaust air did not achieve sufficient changes in the pressure difference on their own.

According to the PFT gas measurement of the transfer air flows between zones, the ratio between the bedroom and living room two-directional transfer air flows fluctuated between 1.3 and 2. According to the PFT and air volume measurements, about 40 - 65% of the supply air in the depressurised bathrooms came as airflow from the living areas and the remainder as leakage air from outside. The ventilation only functions as it is supposed to in houses that are sufficiently airtight. The living spaces were slightly pressurised and some of the supply air was lost to leaks through the living areas' building envelope. The research confirmed findings that mechanical ventilation is much more effective in airtight houses.

Influence of ventilation in the crawl space on radon, microbes and MVOCs

The crawl space pressurisation system with exhaust air from indoors was successful in preventing the convective flow of radon from the soil. However, elevated microbial concentrations were detected in the crawl space, because warm moist air was blown into it promoting favourable conditions for microbial growth.

Carefully balanced separate two-way ventilation in the crawl-space, mechanical supply and exhaust ventilation in the living space and also a tight slab between them appeared to be effective in preventing crawl space air infiltrating into the living space. However, the air change rate of the crawl space, which maintained underpressure relative to indoors, was high in both winter and summer conditions. Thus, this kind of crawl space pressurisation is effective in controlling the level of indoor radon with certain qualifications; the slab must be totally airtight and there should be no organic materials in the filling soil or in the structures of the crawl space.

The simulated effect of different permeabilities of filling soil on convective flow from the soil and on depressurisation of the crawl space

When the simulation assumed that the foundation wall was airtight and the soil's permeability value was $1x10^{-9}$ (m^2) and $1x10^{-8}$ (m^2), a crawl space with an open uncovered ground (gravel) base could be kept depressurised with moderate exhaust ventilation flow.

The effect of the different factors on the hygrothermal conditions and on the sensitivity of mould growth in the crawl space

Theoretically, a microbiologically safe crawl space with both open and closed ground structure was determined with a hygrothermal simulation utilizing the Finnish mould growth model. As a new approach, we used the depressurisation (-10 Pa) of the crawl space in the calculation of hygrothermal conditions and combined this with the mould model.

An open base uncovered ground (air-permeable gravel) in the crawl space is typical in Nordic countries. As a result of the simulation, a crawl space with an open base of uncovered ground can be kept depressurised with moderate exhaust ventilation when the soil's permeability value is $1x10^{-9}$ (m^2) and $1x10^{-8}$ (m^2).

No mould growth was simulated in the examined structures with different air change rate values for building material mould growth sensitivity class 3 (medium resistant; concrete, etc.). Open base uncovered ground is only an effective solution in a crawl space where there are no organic materials. Gravel permeability of $1x10^{-8}$ (m^2) can be regarded as an effective alternative for an open base structure.

The simulation assumed that the perimeter gap between the footer and the ground cover was airtight in an air-sealed ground structure. When the mould growth sensitivity class was set to level 1 (very sensitive: pine wood, etc.), as it is for air-sealed base covered ground, the recommended ground structure is concrete + insulation with an air change rate of 0.2 to 1 h^{-1} for the exhaust air. Another simulation showed that a concrete ground structure with an air change rate of 0.2 to 0.6 h^{-1} was also very effective. Concrete structures have the lowest-risk Mould index due to concrete's moisture capacity, but the Mould index rises if the air change rate is above the recommended level. A ground structure covered by XPS insulation or a plastic vapour barrier resulted in a high Mould index and is thus to be avoided.

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ORIGINAL PUBLICATIONS

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Variation of radon entry rate into two detached houses

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Abstract

The influence of various factors on the concentration of indoor and its variation were investigated statistically in two different types and location of houses. In the single-storey slab-on-grade house (A), the variation of indoor radon closely followed the difference in indoor–outdoor temperature. The measured pressure difference across the wall and wind speed were significant variables ($p < 0.00$), but these factors explained the variation of the radon concentration only slightly. In the two-storey hillside basement house (B), the most significant variable difference in indoor-attic space explained 28% of the variation of the indoor radon. In both houses, the coefficient of determination increased slightly when the average wind speed increased, but in house B the coefficient decreased with high wind speed. In house A, the highest concentration of indoor radon was observed as the wind-induced internal transport of radon. In house B, the highest concentration of indoor radon occurred and the highest coefficient of determination ($100R^2\% = 89\%$) was observed when the wind was blowing towards the slope-side of the esker, causing increased soil gas pressure and air flow in soil. According to this study, the effect of the wind speed on the concentration of indoor radon and on the coefficient of determination was difficult to foresee because the effect of the wind on soil depended strongly on the wind direction and location of the houses. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Radon; Wind; Pressure difference; Temperature; Soil–gas transport

1. Introduction

The transport of radon-bearing gas from the soil into houses is induced by physical and meteorological factors. Radon in buildings is generated by radium decay in soil and building materials. Radon migrates through soil and material pores by gas-phase diffusion. However, the main entry mechanism is the convective flow from the pores in soil through cracks, and the flow increases with increasing negative differences in pressure across the floor and walls (Mowris and Fisk, 1988). Radon concentration in soil gas depends on the radium content and on the emanation coefficient of the soil, whereas the physical characteristics of the soil, such as its grain-size distribution, moisture, porosity and especially the permeability of the soil, determine partly the flow rate of soil gas. Finally, radon enters the house because of pressure differences, caused by temperature difference, wind, barometric pressure and by unbalanced mechanical ventilation and the pressure differences may simply be added together. According to physical models, the pressure difference across a floor follows the difference in indoor–outdoor pressure. The entry rate depends on the type of substructure, its area and tightness.

On the other hand, a rising pressure difference also increases the rate of infiltration of outdoor air through the walls and the ceiling and thus, decreases the concentration of indoor radon due to increasing dilution. In a tight house a mere mechanical exhaust ventilation may, however, induce so large a negative difference in indoor–outdoor pressure that the radon concentration in indoor air may increase due to the increased rate of radon entry. Balanced mechanical exhaust and supply

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ventilation depressurizes the house less than the mechanical exhaust ventilation does, thus it decreases the concentration of indoor radon due to decreased pressure-driven flow of soil gas (Kokotti, 1995).

The pressure induced by wind on the ground near a house may also increase the pressure difference across the floor slab. On the other hand, in very permeable and homogeneous soils, an increase in the wind velocity may lead to decreased radon concentration in soil gas in the vicinity of a house due to wind-induced flushing (Riley et al., 1996). According to many studies the properties of each house as a type, specific location and orientation of the house have a great influence on the concentration of indoor radon. Wind speed and difference in indoor–outdoor pressure are the predominant factors influencing concentrations of indoor and soil radon (Kies et al., 1996). According to them differential pressures and radon concentrations depend mainly on wind direction due to the orientation of the house and the position of openings. Their study also confirms that soil–gas measurements do not necessarily correlate with indoor concentration of radon. On the other hand, Hubbard confirms that changes in the 24 h averaged concentration of indoor radon correlate well with the changes in the radon concentration in soil (Hubbard and Hagberg, 1996). In esker areas, the wind often affects strongly the air flow in soil, but simultaneously with several other factors, such as location of the house on the esker, season and convective subterranean flow of air in the esker (Arvela et al., 1994), therefore, the result is difficult to foresee.

A principal purpose of this study was to investigate statistically the effects of the various factors on the concentration of indoor radon and its variation with continuous measurements in two different types and locations of houses.

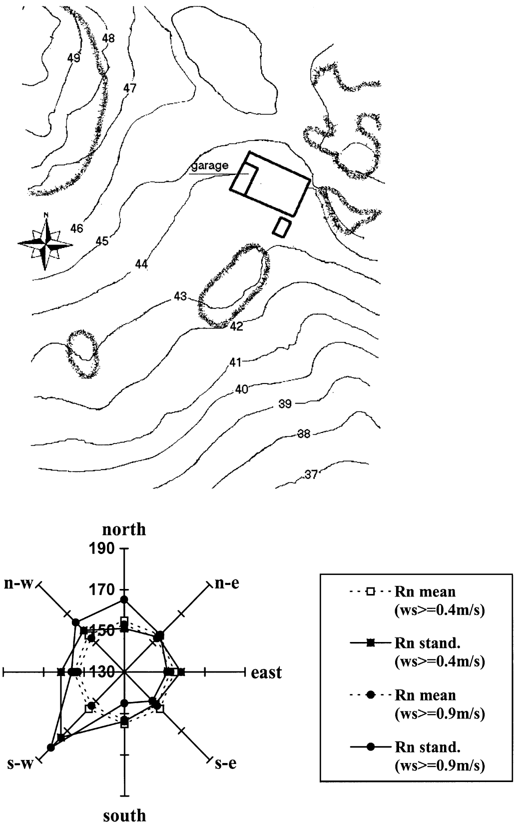

Fig. 1. (Top) The area and location on hillside slope of the slab-on-grade house (A). (Under) Dependence of measured concentration of indoor radon Rn (Bq m^{-3}) on wind direction in house A. The dash line shows the mean value and solid line the adjusted concentration of indoor radon. Analyzed by analysis of covariance.

2. Materials and methods

2.1. The houses and their location on hillside

Both the houses, A and B, were representative of single-family houses in Finland. The single-storey house A (floor area 118 m^2) was located on a gently sloping hillside, where the ground was rocky and composed of coarse material. It was a slab-on-grade house with a gravel layer under the concrete slab as a filling soil. The foundation walls were made of porous light-weight concrete blocks. This kind of foundation is the most common construction in Finland. Both houses were covered with bricks and the load-bearing walls of the houses were build of timber and the houses have a valley roof. The location of the house A is shown in Fig. 1.

The two-storey house B (floor area 188 m^2) was located on the upper north slope of a gravel esker. The walls of its basement extend partly below ground level. The foundation walls were made of similar porous light-weight concrete blocks as in home A. The location of house B is shown in Fig. 2.

Both houses were equipped with mechanical supply and exhaust ventilation systems with heat recovery. The ventilation system was installed in a fireplace room in house A and in a technical room in house B. The ventilation systems were linked by a system of ducts to a series of exhaust and supply vents. Fresh air was introduced into bedrooms, study room, dining room, kitchen and living room through supply vents. The airflow was led from rooms with less moisture sources through gaps under doors (area $\geqslant 160\,cm^2$) to rooms where moisture was produced. Air was exhausted from the main moisture-producing areas (bathroom, sauna, toilet and store room) through exhaust vents (Figs. 3 and 4). The buildings do not have any significant internal resistances so it was assumed that the buildings acted as a single zone.

Characterization of the leakage value of the envelope was performed with a technique called blow-door depressurization test (SIS., 1987). House A was not observed to be especially tight (leakage value Q_{50} is $8.6\,h^{-1}$). House B A was observed to be clearly tighter (Q_{50} is $3.6\,h^{-1}$).

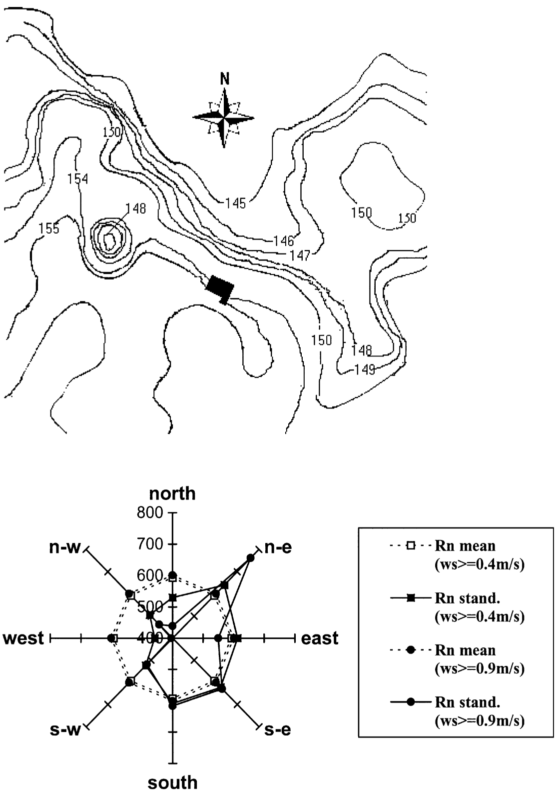

Fig. 2. (Top) The area and location on esker of the two-storey basement house (B). (Under) Dependence of measured concentration of indoor radon Rn ($Bq\,m^{-3}$) on wind direction in house B. The dash line shows the mean value and solid line the adjusted concentration of indoor radon. Analyzed by analysis of covariance.

During the monitoring periods, both houses were inhabited by families, the members of which worked or studied the whole week-days outside the home, thus the occupancy did not affect the ventilation much and the ventilation through the windows was not used.

2.2. Measurements

Both houses were monitored under normal living conditions for long periods. In house A, the measurements were taken in March–August 1993 (a total measuring period of 3616 h); and in house B, the measurements were taken in November 1993, February and March 1994 (the total measuring period of 1131 h).

2.3. Instruments

Data collection system was used for continuous monitoring of the parameters, which are given in Table 1.

The indoor temperature was measured (as 1 h average) 1.1 m above the floor (Figs. 3 and 4) and the outdoor temperature was measured (as 1 h average) by means of a weather station 2 m above the house roof ridge. The outdoor temperature probe was installed in a naturally aspirated shield.

The difference in indoor–outdoor pressure was measured with low differential pressure transducer (SETRA 264, range is $\pm$ 25 Pa with an accuracy of $< \pm 1\%$ from full scale). The pressure difference was measured across the basement wall and also across the roof in open attic space. Polyethylene sampling lines with an inside diameter of $\frac{1}{4}''$ and length 10–25 m were used to connect the pressure from outside the house. The indoor pressure was measured as 0.25 m above the floor in the supply ventilated living room (Figs. 3 and 4) and the outdoor pressure was measured at the same height at the wall.

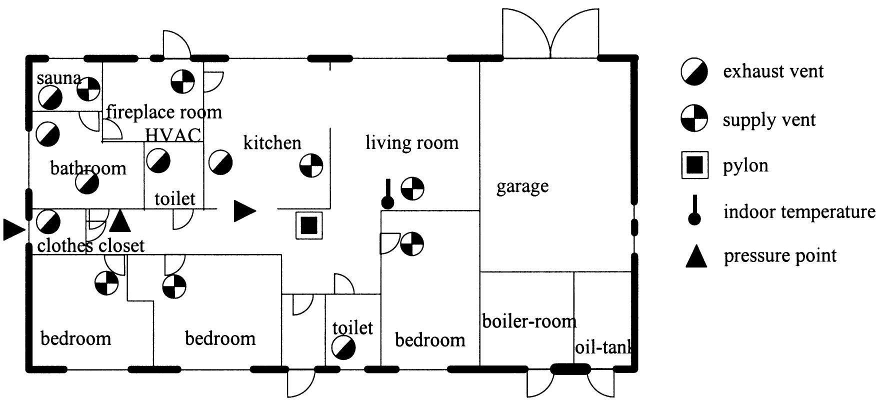

Fig. 3. Floor plan and sampling points of basement of the slab-on-grade house (A).

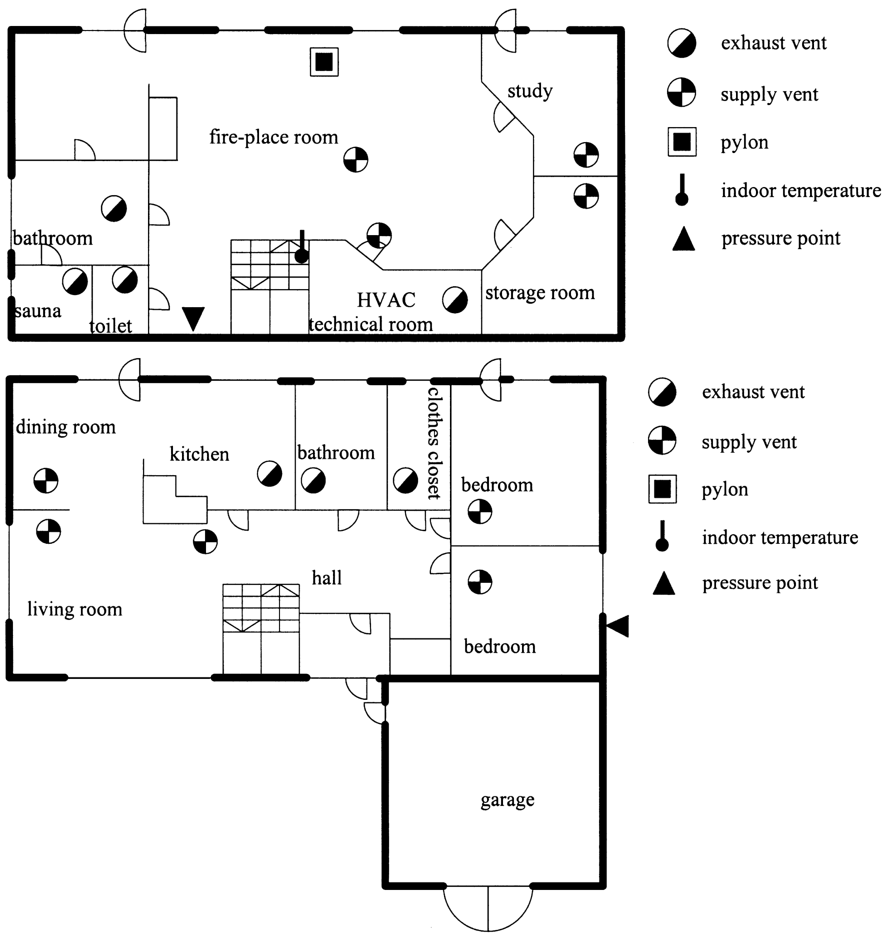

Fig. 4. Floor plan and sampling points of basement of the two-storey basement house (B).

Table 1
Monitored parameters and intervals

Parameter	Measurement system	Measured interval[a] (min)
Indoor temperature	Thermistor, 1.1 m above floor	5/60
Outdoor temperature	Thermistor, in aspirated shield, 2 m above roof ridge	5/60
Pressure difference	Low differential pressure transducer	5/60
Supply and exhaust flow rate	Halton MSD-device through main ducts	5/60
Indoor radon	Lucas scintillation cell	30/60
Local wind speed and direction	Cup anemometer, 2 m above roof ridge	5/60

[a]Measured 5 or 30 min average, calculated for 60 min.

The low-pressure differences are difficult to measure accurately because the result depends on the location of the measuring point at the wall and on the direction of the wind. For comparison the pressure difference was measured also in an open attic space which had been found to abate well the effect of the wind fluctuations in Finnish study (Korkala and Siitonen, 1986; Karvonen and Virtanen, 1988).

Mechanical supply and exhaust flow rates (mechanical air-exchange rate) of air through main ducts were measured with measurement devices of flow rate of air volume (Halton MSD, accuracy of the measurement $< 5\%$) which were based on the pressure difference caused by air flow. The measurement device was connected to pressure transducer (SETRA 264, the range is 125 Pa with an accuracy of $< \pm 1\%$ from full scale).

Radon concentration analyzed by using Lucas scintillation cell method (Lucas, 1957) is included in the Pylon AB-5 portable radiation monitor assembly (Vandrish and Lebel, 1986). Radon concentration was measured to be 1.1 m above the basement floor (Figs. 1 and 2).

Local wind speed/direction and temperature were measured by means of a weather station 2 m above the house roof ridge as 5 min averages. Wind direction and 1 h averages were calculated by using Yamartino method (Turner, 1986).

The principle of continuous ventilation control system and the data collection system have previously been presented in more detail (Kokotti et al., 1994).

2.4. Formation of data and data analysis

The data of various physical factors and the concentration of indoor radon were analysed by linear correlation analysis, multiple regression analysis and analysis of covariance. The association between the various physical factors and the concentration of indoor radon was investigated by multiple regression analysis, using a stepwise method (Armitage and Berry, 1994). The criterion for a variable to be included was that its partial regression coefficient must be significant at the 0.05 level, and a variable was eliminated if its partial regression coefficient failed to be significant at the 0.1 level. The physical factors were the difference in indoor–outdoor temperature, difference in indoor–outdoor pressure, meteorological factors and ventilation. The measured ventilation rate did not include infiltration by natural ventilation caused by wind and temperature difference; but these factors were studied with statistical analysis.

In multiple regression analysis, the coefficient of determination $100R^2\%$ (defined by the multiple correlation R) indicated the goodness of fit of the regression models. Dependence of concentration of indoor radon on wind direction, was investigated by the analysis of covariance, by which the deviations of the adjusted group (wind direction $1 \ldots 8$, $v \geqslant 0.4\,\mathrm{m\,s^{-1}}$) means from the grand mean were also calculated. A wind direction is a circular function with a crossover point between 360 and 0°; therefore, standard statistical methods for linear data set are not applicable but the Yamartino method was used when the arctangent of the mean sines and cosines was calculated (Turner, 1986).

3. Results and discussion

3.1. Variation of the concentration of indoor radon

In the single-storey slab-on-grade house (A), the variation of the concentration of indoor radon closely followed the indoor–outdoor temperature differences with a positive correlation coefficient ($r = 0.74$) (see Figs. 5 and 6). However, the radon concentration varied a lot. According to the multiple regression analysis, the difference in indoor–outdoor temperature was the most significant variable ($p < 0.00$) to explain the concentration of indoor radon. The coefficient of determination was 55% based on the multiple correlation square. When used for the difference in indoor–outdoor temperature and the supply air flow in the analysis, the coefficient of determination was 63% and for all variables in the analysis, the coefficient of determination became only slightly higher, 65%. The variables were the difference in indoor–outdoor temperature, difference in indoor–outdoor pressure, supply and exhaust air flows and wind speed. In

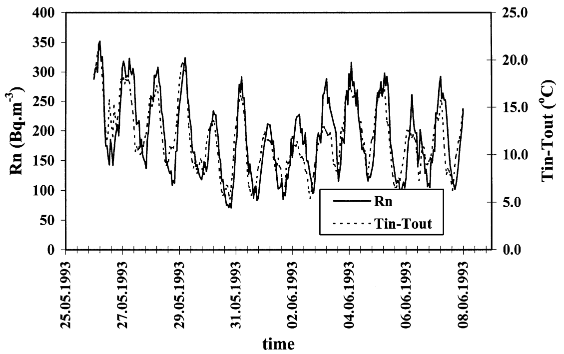

Fig. 5. The variation of concentration of indoor radon (Bq m^{-3}) and difference in indoor–outdoor temperature T_{in}–T_{out} (°C) vs. time during two weeks in the slab-on-grade house (A).

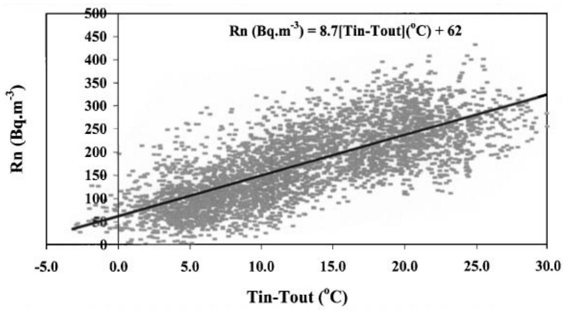

Fig. 6. Dependence of measured concentration of indoor radon Rn (Bq m^{-3}) on difference in indoor–outdoor temperature T_{in}–T_{out} (°C), based on 3616, 1 h average measurements in the slab-on-grade house (A).

Table 2
The mean, standard deviation s, regression coefficient B and standardized coefficient beta from the following factors: difference in indoor–outdoor temperature T_{in}–T_{out} (°C), wind speed W_s (m s^{-1}), difference in indoor–outdoor pressure PD_{in-out} (Pa), difference in indoor–attic space pressure $PD_{in-attic}$ (Pa), flow rate of mechanical exhaust Q_e (m^3 h^{-1}), flow rate of mechanical supply Q_s (m^3 h^{-1}) and concentration of indoor radon Rn (Bq m^{-3})

Variable	House A	House B
T_{in}–T_{out} (°C)		
Mean/s	12.7/6.9	29.4/4.3
B	6.58	—
Beta	0.559	—
W_s (m s^{-1})		
Mean/s	0.5/0.5	1.0/0.8
B	− 12.02	—
Beta	− 0.082	—
PD_{in-out} (Pa)		
Mean/s	0.0/0.4	0.5/1.0
B	− 24.98	− 19.4
Beta	− 0.116	− 0.145
$PD_{in-atticspace}$ (Pa)		
Mean/s	0.2/0.4	1.2/0.9
B	− 5.00	− 60.3
Beta	0.025	− 0.415
Rn (Bq m^{-3})		
Mean/s	173/81	603/134
Q_s (m^3 h^{-1})		
Mean/s	149/20	277/20
B	− 1.38	− 1.06
Beta	− 0.342	− 0.159
n (h^{-1})	0.51	0.57
Q_e (m^3 h^{-1})		
Mean/s	164/19	262/19
B	0.50	—
Beta	0.117	—
n (h^{-1})	0.56	0.54

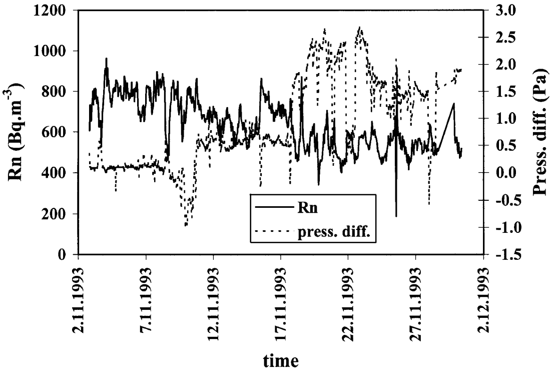

Fig. 7. The variation of concentration of indoor radon (Bq m^{-3}) and difference in indoor–outdoor pressure $PD_{in\text{-}out}$ (Pa) vs. time during one month in the basement house (B).

house A the highest multiple correlation (− 0.30) was between the wind speed and the pressure difference across the wall and thus, the house had no problem with collinear variables. The pressure difference across the wall was a significant variable ($p = 0.02$) to explain the concentration of indoor radon and the concentration increased when the pressure difference increased, but the measured pressure difference explained the variation of the radon concentration only slightly. It was possible that the measured (1-h average) pressure difference across the wall and the pressure difference across the floor slab did not correlate well with each other. In such a leaky house as A (n_{50} is 8.6 h^{-1}) the low difference in indoor–outdoor pressure does not necessarily create any significant pressure difference across the floor. The measured pressure difference was also rather low (0 … 0.4 Pa) (Table 2). It is, therefore, possible that the concentration of indoor radon which depends mainly on the pressure difference across floor cannot be explained precisely by the difference in indoor–outdoor pressure as the physical models have been shown. In addition, infiltration caused by stack effect affects the dilution of indoor radon and thus, also the concentration of indoor radon. However, the variation of the concentration of indoor radon closely followed the indoor–outdoor temperature differences. In addition, the concentration of indoor radon was observed to have a 2–3 h delay. When this was taken into account in the multiple regression analysis; it increased the coefficient of determination by about 10%. The time delay was induced mainly by the slow change in indoor concentration of radon caused by the diurnal change in natural ventilation rate and may also have been induced by a crack in the rock, which acted as a limited radon source beneath the gravel layer.

In the two-storey house (B) with basement (n_{50} is 3.6 h^{-1}), the concentration of indoor radon followed the fluctuations of indoor-attic space pressure difference with a negative correlation coefficient ($r = -0.57$), but the radon concentration varied a lot (see Figs. 7 and 8). The pressure difference across the roof was the most significant variable ($p < 0.00$) for the concentration of indoor radon and the pressure difference explained 33% of the variation of the radon concentration. The coefficient of determination became only slightly higher for all significant variables; the pressure difference and the flow of supply air, 35%. In addition, the multiple regression analysis indicated that the pressure difference across the roof in open attic space explained the concentration of indoor radon more than the pressure difference across the wall did. Furthermore, pressure differences across the

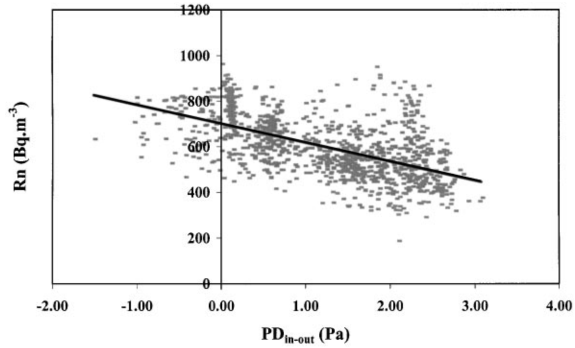

Fig. 8. Dependence of measured concentration of indoor radon Rn (Bq m^{-3}) on difference in indoor–outdoor pressure PD_{in-out} (Pa), based on 1131, 1 h average measurements in the basement house (B).

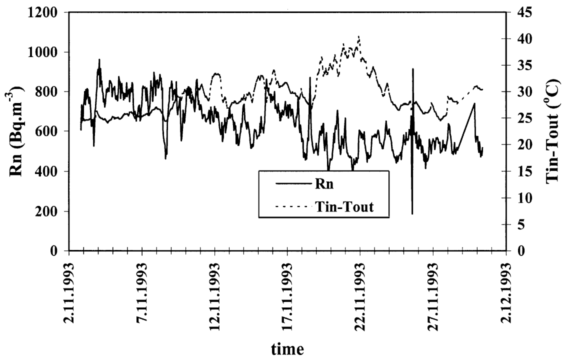

Fig. 9. The variation of concentration of indoor radon (Bq m^{-3}) and difference in indoor–outdoor temperature T_{in}–T_{out} (°C) vs. time during one month in the basement house (B).

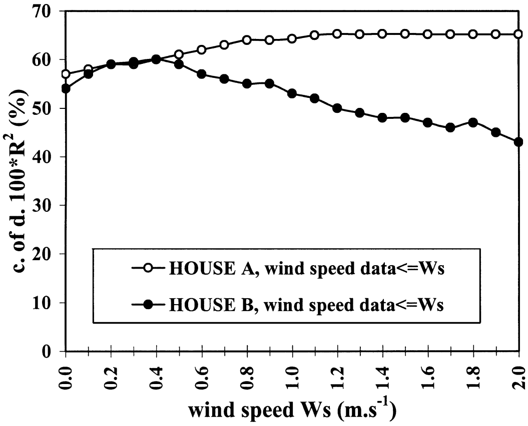

Fig. 10. Dependence of coefficient of determination (C or D) on wind speed W_s (m s^{-1}) in the slab-on-grade house (A) and in the basement house (B).

roof were higher because in both houses the attic space abated the effect of wind fluctuation (Table 2). Obviously, many factors affect the concentration of indoor radon simultaneously. In house B the highest multiple correlation (0.53) was between the temperature difference and the pressure difference across the wall. However, the difference in indoor–outdoor temperature and the concentration of indoor radon correlated negatively ($r = -0.28$), but it was not a significant variable ($p > 0.05$) according to the multiple regression analysis to explain the radon concentration (Fig. 9).

In the basement house (B), diurnal variations in the rate of radon entry were negligible, and there was no observed time delay in the rate of radon entry. This may be due to the small and irregular variation in the measured temperature difference (Table 2) and the observed sensitivity of radon to the effect of wind.

In both houses, the multiple regression analysis indicated that the flow of supply air affected both dilution and concentration of indoor radon more than the flow of exhaust air did. This is shown by the standardised coefficients in Table 2. In both houses the standardized coefficient beta (absolute value) of mechanical supply flow was higher than the coefficient beta of mechanical exhaust flow. Furthermore, when the supply air increased, the indoor concentration of radon decreased, and when the exhaust air increased, the indoor concentration of radon increased because in both houses the regression coefficient of mechanical supply flow was negative and the mechanical exhaust flow was positive (Table 2). In both houses the effect of the flow of exhaust and supply air on the indoor air concentration would have been still more distinct if the ranges of the flows of air had been wider. The variations in the mechanical supply and exhaust flow were minor, which is seen in the small values for their standard deviations (Table 2).

3.2. *Effect of the wind speed*

In both the houses, the wind speed affected the concentration of radon, and the coefficient of determination depended on the wind speed. However, the effect of the wind speed on the concentration of indoor radon was difficult to foresee because the effect of the wind depended strongly on the wind direction. In this study the effect of the wind on the coefficient of determination was studied by classifying the data according to the wind speed and the coefficient of determination was analyzed separately in each class of data.

In the slab-on-grade house (A) the coefficient increased slightly when the average wind speed increased (Fig. 10).

Also in the basement house (B), the wind effect was at first observed with low wind speed, but the coefficient decreased with high wind speed. The highest coefficient of determination was 60% when the mean wind speed

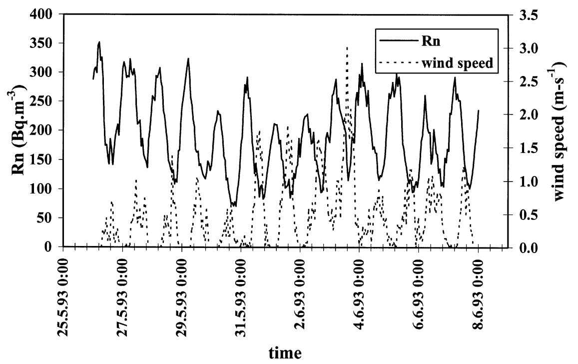

Fig. 11. The variation of concentration of indoor radon (Bq m^{-3}) and wind speed (m s^{-1}) vs. time during two weeks in the slab-on-grade house (A).

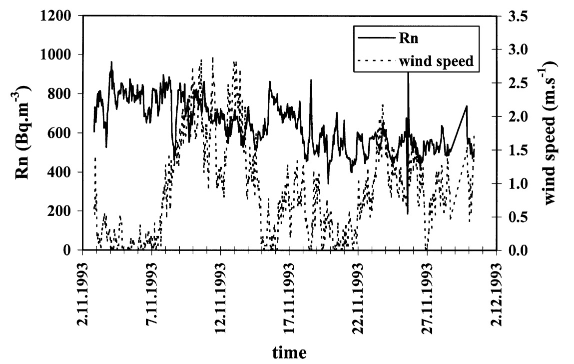

Fig. 12. The variation of concentration of indoor radon (Bq m^{-3}) and wind speed (m s^{-1}) vs. time during one month in the basement house (B).

was no more than 0.4 m s^{-1} (Fig. 10). The coefficient became smaller due to the effect of the wind on the esker when the wind speed increased further.

The coefficient of determination decreased with high wind speed because wind affected the flow of soil gas, and the radon concentration in soil pores. For this reason, the variable factors investigated in this study explained only part of the concentration of indoor radon.

The concentration of indoor radon does not necessarily increase evenly with increasing difference in indoor–outdoor temperature when the temperature difference remains small, because at the same time the radon concentration due to diffusion decreases with increasing temperature difference and wind speed. The radon concentration increases with increasing temperature difference. The increased radon concentration is caused by the increasing pressure-driven flow from soil into the house. The increased coefficient of determination was possibly due to the decrease in proportion of the diffusive source from the source combination when the temperature difference and the wind speed increased. Arvela and Winqvist (1989) reported the dependence between diffusive and convective sources using a prediction model for indoor radon. The results of the statistical analysis are analogous with their model. The source combination did not increase linearly when the temperature difference was small and the coefficient of determination of the analysis, therefore remained small.

In the slab-on grade house (A) concentration of indoor radon decreased slightly when the average wind speed increased (Table 2) and the wind speed correlated negatively ($r = -0.175$) with the concentration of indoor radon. The variation of the wind was mainly diurnal (Fig. 11). According to the multiple regression analysis, the wind speed was the significant variable ($p < 0.00$) to explain the concentration of indoor radon. However, the standardized coefficient beta (absolute value) of wind speed was smaller than the coefficient beta of other variables (Table 2) and thus the wind speed explained the concentration of indoor radon only slightly. In addition the variation of the wind speed and temperature difference were typically simultaneous and the temperature difference explained mostly the variation of the concentration of indoor radon.

In the basement house (B) the wind speed did not affect the mean value of concentration of indoor radon because the radon concentration in the groups of the wind speed did not differ from each other (Table 2). Furthermore, according to the multiple regression analysis, the wind speed was not the significant variable ($p > 0.05$) to explain the concentration of indoor radon which is seen in Fig. 12.

3.3. *Effect of wind direction*

As mentioned above, the effect of the wind speed on the concentration of indoor radon and on the coefficient of determination was difficult to foresee because the effect of the wind depended strongly on the wind direction in the esker area.

In the slab-on-grade house (A), the analysis of covariance indicated that the highest concentration of indoor radon (19% over grand mean) was observed when the wind came from a certain direction (south-west) and probably induced the transport of radon-containing air from the nonventilated garage through the wall or floor constructions to the adjacent living-room (Fig. 1). In this direction infiltration through the walls and the ceiling due to wind was the highest and thus, the concentration of indoor radon could be even higher if the envelope was tighter. The mean values of the concentration of indoor radon (Rn = 153 Bq m^{-3}) with two wind speeds ($v \geqslant 0.5$ and 0.8 m s^{-1}) were the same. Also the wind direction did not affect the coefficient of determination. In the analysis

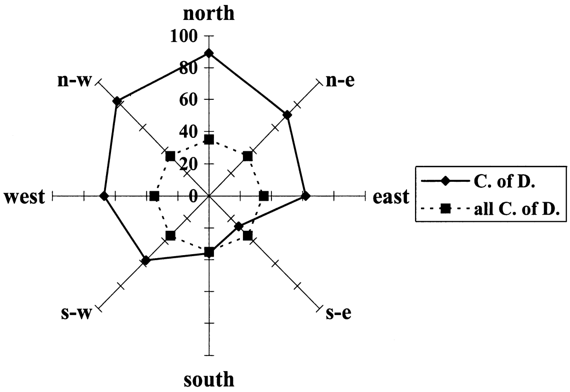

Fig. 13. Coefficient of determination (C or D) in the house B as a function of wind direction.

of covariance the main effect and covariates were significant ($p < 0.00$) in both houses.

In the basement house (B), the highest concentration of indoor radon (27% over grand mean) occurred when the wind direction was perpendicular to the esker, leading to increasing soil gas pressure and consequently to increased radon entry and concentration (Fig. 2). In this direction the infiltration and dilution of indoor radon due to wind was also the highest. Also the highest coefficient of determination ($100R2\% = 89\%$) with respect to wind directions was observed when the wind was blowing towards the slope side of the esker (Fig. 13). This wind direction affected mainly the basement room which have only mechanical supply vents. It was, therefore, possible that the supply air from the basement carried a flow of radon-bearing air to the upstairs. The relation of the long-term radon levels (four months) between the upstairs living-room and the basement was 0.8. The radon concentration was higher in the basement than upstairs although the two storeys were connected by an open stairwell. An explanation for this may have been the better dilution caused by the supply air in the upstairs than in the basement. The lowest concentration of indoor radon (33% under grand mean) was observed when the wind was blowing from an opposite direction from the top of the esker. When the wind was blowing in this direction it had no strong effect on the flow in the slope of the esker, but it possibly increased the rate of radon entry into the bathroom, the sauna and the toilet equipped only with exhaust vents. The radon transportation from the moist rooms depressurized by exhaust ventilation, to upstairs pressurized by supply air, was negligible as opposed the transportation from the pressurised basement room. The mean values of concentration of indoor radon ($Rn_{0.4} = 594\,Bq\,m^{-3}$ and $Rn_{0.9} = 604\,Bq\,m^{-3}$) with two wind speeds ($v \geqslant 0.4$ and $0.9\,m\,s^{-1}$) were almost the same.

4. Conclusions

According to this study, many factors might simultaneously affect the concentration of indoor radon and the coefficient of determination which cannot be observed merely by single factors as the difference in indoor–outdoor pressure. In this study the permeability of the soil, properties of the houses as terrain in the vicinity of a house, location, orientation and characteristics of the house were the main factors. These factors together with physical and meteorological factors affected mainly the variation of the concentration of indoor radon.

This study showed that in the case of the basement house (B), which was located on the upper slope of a gravel esker, the main factor was the fluctuating wind blowing toward the permeable esker. This factor, together with the convective subterranean air-flow in the esker, affect the pressure difference across the under ground structure, the flow of soil gas, and the radon concentration in soil pores. However, the effect of the wind speed on the concentration of indoor radon and the coefficient of determination was difficult to foresee because the effect of the wind in soil depended strongly on the wind direction. For this reason, when all the wind directions observed were included the difference in indoor–outdoor pressure explained only 33% of the concentration of indoor radon and the all variable factors 35% respectively.

In the case of the slab-on-grade house (A), the effect of these factors are not significant because the house is located on a gently sloping rocky surface. Thus, the movement of the wind through the top soil generally has only a limited effect on the pressure conditions in the soil. In this house, the concentration of indoor radon was the highest in windy conditions when the wind probably induced the transport of the air containing radon from one room to another or beneath the slab.

Acknowledgements

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II

Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P.

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Effect of various factors on the rate of radon entry into two different types of houses

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Abstract

Various factors that affect the rate of radon entry were investigated in two detached hill-side houses. In the slab-on-grade house (A), this rate reached its maximum value during a particular weather condition when the wind-induced internal transport of radon, whereas the rate of radon entry into the basement house (B) on the upper slope of a esker was highest when the wind was blowing towards the esker. In neither house did changes in barometric pressure measured at 3 h intervals influence the radon entry rate. Nor did rain influence the rate of radon entry into house A. In house A, the radon entry rate was observed to have a 2–3 h delay; and after it was adjusted by the analysis of covariance, the radon entry rate was higher in the morning and lower in the evening. In house B, however, diurnal variations in the radon entry rate were negligible. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Radon; Physical factors; Meteorological factor; Time delay of radon entry; Soil–gas transport

1. Introduction

Radon is a noble radioactive gas that is formed in radium-bearing materials in soil and buildings. The health risk caused by radon in indoor air results from the high-energy alpha particles radiated by the two particular decay products of radon. When deposited in the bronchi and alveoli from inhaled air, these small radioactive particles damage the bronchial and alveolar tissues.

The transport of radon-bearing gas from the soil into houses is induced by physical and meteorological factors. Concentration of indoor radon depends on two factors: (1) convective flow from the soil pores through cracks of the floor and the lower part of the building envelope and (2) diffusion from building materials and soil. Convective flow increases with increasing negative differences in pressure across the substructure [1]. Radon concentration in soil depends mainly on only two parameters: radium content and the emanation coefficient of the soil, whereas the flow rate of radon-bearing gas from in the soil is affected by many characteristics which also depend on each other, such as grain size, distribution, moisture, porosity and the permeability of the soil. Radon entry depends on the difference in pressure across a basement floor and the leakage area of the substructure. The difference in indoor–outdoor pressure is caused by temperature difference, wind, barometric pressure and unbalanced mechanical ventilation, and the pressure differences can be estimated as the sum effect, i.e. the total difference in pressure. According to physical models, the pressure difference across a floor follows the difference in indoor–outdoor pressure [1].

The difference in pressure increases the rate of infiltration and thus decreases the indoor concentration of radon. In a tight house, however, mechanical exhaust ventilation may increase the rate of radon entry due to the rising negative difference in indoor–outdoor pressure. Balanced mechanical exhaust and supply ventilation depressurises the house less than the mechanical exhaust ventilation does, thus decreasing the concentration of indoor radon due to decreasing pressure-driven flow of soil gas [2].

The pressure induced by wind on the ground near a house may also increase the pressure difference across the floor slab. On the other hand, in very permeable and homogeneous soils, an increase in wind velocity may lead to decreased radon concentration in soil gas in the vicinity of a house due to wind-induced flushing [3]. In esker areas, the wind affects the air flow in soil, radon concentration in soil pores and

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Nomenclature

AP	barometric pressure (Pa)
d	decay rate of radon (0.0076 h^{-1})
n_{50}	air change rate at 50 Pa pressure difference (h^{-1})
n	air-exchange rate (h^{-1})
Pd_{in-out}	difference in indoor–outdoor pressure (Pa)
Q_s	flow rate of mechanical supply (m^3 h^{-1})
Q_e	flow rate of mechanical exhaust (m^3 h^{-1})
R_{ni}	indoor radon concentration (Bq m^{-3})
R_{no}	outdoor radon concentration (Bq m^{-3})
S	rate of radon entry (Bq m^{-3} h^{-1})
S_a	rate of radon entry, convective radon source (Bq m^{-3} h^{-1})
S_p	rate of radon entry, diffusive radon source (Bq m^{-3} h^{-1})
T_{in}	indoor temperature (°C)
T_{out}	outdoor temperature (°C)
W_s	wind speed (m s^{-1})

the concentration of indoor radon when the wind is blowing toward the esker slopes. The observed high concentrations of radon in houses on eskers cannot be explained merely by variations in the radon concentration of the air in the soil. The subterranean flow of air must also increase the pressure difference, thus driving the air from the soil into houses [4].

Several other factors, such as changes in barometric pressure and precipitation, may influence the flow of radon-bearing gas from the soil into the house. A heavy rainfall potentially increases the rate of radon entry. One might expect that changes in barometric pressure would increase the radon entry rate through the substructures in those cases where the soil permeability is high and the surface of the soil is frozen or filled tightly with soil. However, Nazaroff et al. (1985) found no statistical connection between a change in barometric pressure and the radon concentration of gas in the soil [5]. In houses with a crawl space, however, after heavy rains concentrations of radon were high [6]. During and after rain, the permeability of the soil on the surface of the soil decreases compared to the dry soil under the floor slab. This may cause a short-term increase in radon concentration regardless of changes in barometric pressure. On the other hand, Hintenlang and Al-Ahmady (1992) observed that when the permeability of the soil was low, the semi-diurnal variations of atmospheric pressure could provide an additional source of radon entry. Semi-diurnal variation in barometric pressure is the result of atmospheric tides resulting from solar heating and coriolis forces on the Earth. These naturally induced differences in pressure could make major contributions to radon entry when other sources of house pressurization or depressurization, and consequently the infiltration rate of outdoor air, are small [7]. Robinson et al. (1997) reported that, both theoretically and experimentally, fluctuations in atmospheric pressure can cause radon to enter a house without differences in indoor–outdoor pressure. The flow rate of soil gas induced by a change in atmospheric pressure depends on both the characteristic response time of the soil and the time-rate-of-change of the fluctuation in atmospheric pressure. Spectral analysis indicates that the relatively low-frequency fluctuations in atmospheric pressure, less than 100 times per day, are the most important reason for gas flow into a house from the soil [8].

2. Materials and methods

2.1. Study buildings

Both houses (A and B) are located on a hill-side (Figs. 1 and 2) in southern Finland. The houses were representative of single-family houses in Finland. The ground beneath the single-storey house (A) is rocky and composed of coarse material. Under the slab, which was constructed from poured concrete, there is a gravel layer used as filling soil. In both houses, the foundation walls are, made of porous light-weight concrete blocks. The houses were covered with bricks, load-bearing walls of the house were built of timber and the houses have a valley roof. The two-storey house (B) is located on the upper north slope of a gravel esker. The walls of its basement extends partly below the ground level. These two houses had different values for air leakage n_{50} (A, 8.6 h^{-1}, B, 3.6 h^{-1}), even though they were both equipped with in-blow and exhaust systems of ventilation.

The houses had two adult and two children, both of whom worked and study full-time outside the home so that occupancy did not affect ventilation a lot during and they did not used ventilation through the windows or doors during the measuring periods.

2.2. Measurements

Both houses were monitored for long-measuring periods. In house A, the measurements were taken during March to August (a total measuring period of 3616 h); and in house B, the study lasted from November to March (a total measuring period of 1131 h).

2.3. Instruments

The continuous measurements included: indoor temperature (as 1 h average; measured 1.1 m above the floor),

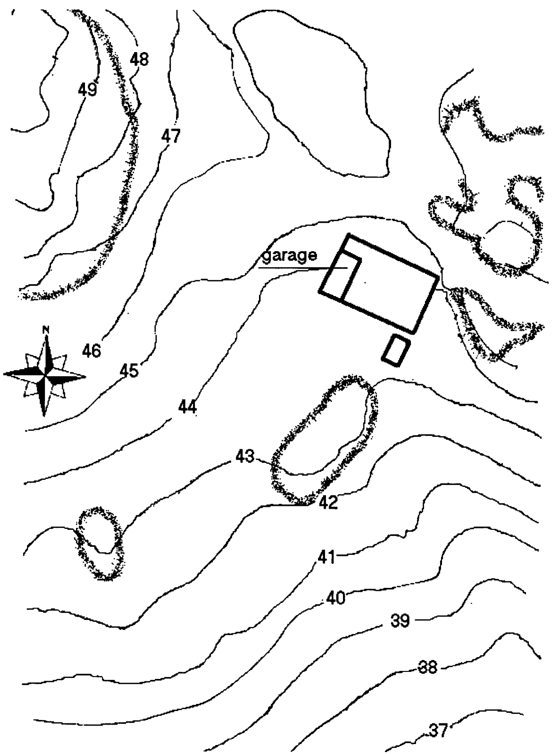


Fig. 1. Top: The area and location on the hill-side slope of the slab-on-grade house A.

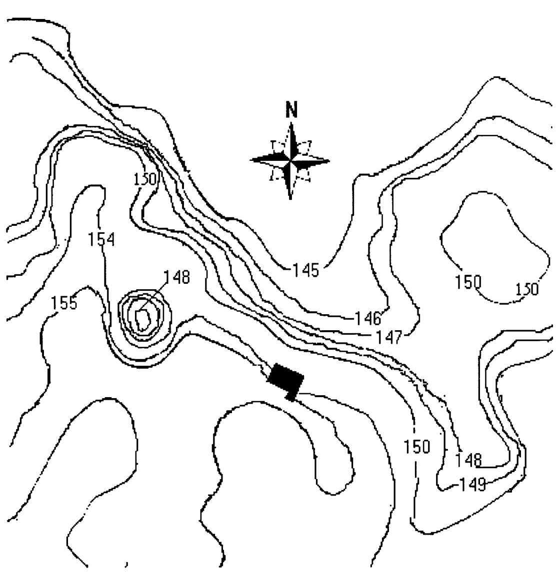


Fig. 2. Top: The area and location on the esker of the basement house B.

difference in indoor–outdoor pressure measured with a low differential pressure transducer (SETRA 264, range ±25 Pa with a accuracy of $< \pm 1\%$ from full scale), mechanical supply and exhaust flows measured with orifice plates (accuracy of $< 5\%$) connected to a pressure transducer (SETRA 264, range 125 Pa with a accuracy of $< \pm 1\%$ from full scale), and short-term radon concentrations were analysed using the Lucas scintillation cell method, which is included in the portable assembly of the radiation monitor (Pylon AB-5). The long-term radon concentrations for 1 month concentrations were analysed by nuclear track dosimeters at the Finnish Centre for Radiation and Nuclear Safety.

Local wind speed/direction and temperature were measured (as 1 h averages) by a weather station 2 m above the house roof. Absolute ambient atmospheric pressure and precipitation were obtained from the meteorological station of the nearest airport as 3 h averages.

The system of the continuous ventilation control system and data collection system has previously been presented in more detail [9].

2.4. Formation of data and data analysis

The rate of radon entry S has a diffusive radon source S_p, which is assumed to be constant and convective source S_a, which is assumed to be proportional to the air-exchange rate (Nazaroff et al., 1985).

These radon sources are summarized by the following equation:

$$S = S_p + S_a(\Delta P_f), \tag{1}$$

where ΔP_f denotes the pressure difference across a floor. The difference in indoor–outdoor pressure is caused by temperature difference, wind, barometric pressure and unbalanced mechanical ventilation.

The indoor concentration of radon in steady state is given by following equation:

$$R_{ni} = \frac{S + R_{no} \times n}{n + d}, \tag{2}$$

where R_{ni} is the indoor radon concentration (Bq m^{-3}), R_{no} is the outdoor radon concentration (Bq m^{-3}), n is the air-exchange rate (h^{-1}) which is Q/V, Q is the supply air rate (m^3 h^{-1}), V is the volume of the house (m^3) and d is the decay rate of the radon (h^{-1}). In Finnish houses air exchange rates has to be greater or equal than 0.5 h^{-1}, the decay rate of radon $d \ll n$. Also, the outdoor radon concentration $R_{no} \ll$ indoor radon concentration R_{ni}. Assuming these simplifications, the rate of radon entry S (Bq m^{-3} h^{-1}) was calculated as follows [5]:

$$S = R_{ni} \times n \text{ (Bq m}^{-3}\text{ h}^{-1}\text{)}. \tag{3}$$

Eq. (3) determines only the dilution of ventilation but does not determine all effects of the various factors on the rate of radon entry and its variation, such as time dependence and the characteristic pressure difference. These factors and their effect on the rate of radon entry are studied with statistical analysis.

Rain data were generated as follows: 0 = no rain, 1 = before rain, 2 = rain and 3 = after rain.

The time delay: $m_{1\ldots}$ = hourly average of the variable (for example, difference in indoor–outdoor temperature) and $S_{1\ldots}$ = hourly average for rate of radon entry.

The time delay between rate of radon entry (S) and the variables (m) was generated in the following way:

2 h time delay, for example,

variable m	rate of radon entry S
m_1	S_3
m_2	S_4
...	...

Changes in barometric pressure, dt AP, and rate of radon entry, dt S, were generated in the following way:

variable dt AP	variable dt S
$AP_1 - AP_2 = dt\ AP_{1-2}$	$s_1 - s_2 = dt\ S_{1-2}$
$AP_2 - AP_3 = dt\ AP_{2-3}$	$s_2 - s_3 = dt\ S_{2-3}$
...	...

The data of various factors and the rate of radon entry were analysed by linear correlation analysis, multiple regression analysis and analysis of covariance. The association between the various physical factors and the entry rate of indoor radon was investigated by multiple regression analysis, using a stepwise method [10]. The criterion for a variable to be included was that its partial regression coefficient must be significant at the 0.05 level, and a variable was eliminated if its partial regression coefficient failed to be significant at the 0.1 level. The physical factors were difference in indoor–outdoor temperature, difference in indoor–outdoor pressure, meteorological factors and ventilation. In multiple regression analysis, the coefficient of determination $100R^2$ (defined by the multiple correlation R) indicated the goodness of fit of the regression models. In addition to this, standardized coefficients (beta) were used for mutual comparison of the explanatory variables. Dependence of radon entry rate on wind direction, rain and diurnal variation was investigated by analysis of covariance, by which the deviations of the adjusted group means from the grand mean were also calculated.

3. Results and discussion

3.1. Variation in rate of radon entry

According to the multiple regression analysis, the difference in indoor–outdoor temperature was the most significant variable ($p < 0.00$) for explaining the rate of radon entry into the slab-on-grade house (A). The coefficient of determination was 53%. When used for all variables, the coefficient of determination became only slightly higher, 57%. The variables were difference in indoor–outdoor temperature, difference in indoor–outdoor pressure and wind speed. Unexpectedly, the indoor–outdoor difference in pressure was not a significant variable ($p > 0.05$). Thus, in such a leaky house as A (n_{50} is 8.6 h^{-1}) the low positive difference in indoor–outdoor pressure (Table 1) does not necessarily create any significant pressure difference across the floor.

Table 1

The mean, standard deviation s, regression coefficient B and standardized coefficient beta from the following factors: difference in indoor–outdoor temperature $T_{in} - T_{out}$ (°C), wind speed W_s (m s^{-1}), difference in indoor–outdoor pressure PD_{in-out} (Pa), flow rate of mechanical exhaust Q_e (m^3 h^{-1}), flow rate of mechanical supply Q_s (m^3 h^{-1}), radon entry rate S (Bq m^{-3} h^{-1}) and barometric pressure AP (Pa n^{-1})

Variable	House A	House B
$T_{in} - T_{out}$ (°C)		
Mean s^{-1}	12.7/6.9	29.4/4.3
B	3.50	—
Beta	0.67	—
W_s (m s^{-1})		
Mean s^{-1}	0.5/0.5	1.0/0.8
B	−2.42	—
Beta	−0.037	—
$PD_{in\text{-}out}$ (Pa)		
Mean s^{-1}	0.2/0.4	1.2/0.9
B	−14.02	−31.3
Beta	−0.146	−0.39
S (Bq m^{-3} h^{-1})		
Mean s^{-1}	85/35	340/75
AP (10^2 Pa)		
Mean s^{-1}	1012.6/9.7	1023.8/17.7
Q_s (m^3 h^{-1})[a]		
Mean s^{-1}	149/20	277/20
B	−1.12	−1.23
Beta	−0.28	−0.19
Q_e (m^3 h^{-1})[a]		
Mean s^{-1}	164/19	262/19
B	0.58	0.47
Beta	0.14	0.07

[a]used radon concentration in the analysis instead of the rate of radon entry.

In the two-storey house with the basement (B) (n_{50} is 3.6 h^{-1}) the difference in indoor–outdoor pressure was the most significant variable ($p < 0.00$) for radon entry rate, but the model explained the radon entry rate only slightly ($100R^2 = 28\%$). The coefficient of determination became only slightly higher for all variables, 29%. Obviously, many factors affect the radon entry rate simultaneously.

In both houses, the multiple regression analysis indicated that the supply air flow affected both dilution and entry of radon concentration more than the flow of exhaust air did. This is shown by the standardized coefficients in Table 1. In both houses, the standardized coefficient beta of mechanical supply flow was higher than the coefficient beta of mechanical exhaust flow. Furthermore, when the supply air increased, the indoor concentration of radon decreased, and when the exhaust air increased, the indoor concentration of radon increased because in both houses the regression coefficient of mechanical supply flow was negative and the mechanical exhaust flow was positive (Table 1). In both houses the effect of the flow of exhaust and supply air on the indoor air concentration would have been still more distinct if the ranges of the flows of air had been wider. The variations in the mechanical supply and exhaust flow were minor, which is seen in the small values for their standard deviations (see Table 1).

3.2. Effect of wind

In both houses, wind speed affected the rate of radon entry and the coefficient of determination depended on wind speed. In both houses, the coefficient increased slightly when the average wind speed increased, but in the basement house (B) the coefficient decreased with high wind speed.

In the slab-on-grade house (A), the analysis of covariance indicated that the highest rate of radon rate was observed when the wind came from a certain direction and probably induced the transport of radon-containing air from the garage through the wall or floor constructions to the adjacent living-room. On the other hand, the wind direction did not affect the coefficient of determination.

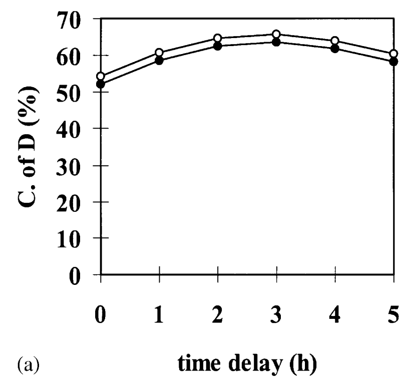
In the basement house (B), the highest rate of radon entry occurred when the wind direction was perpendicular the esker, leading to increasing pressure of soil gas and consequently to increased rate of radon entry. The highest coefficient of determination ($100R^2 = 82\%$), with respect to wind direction, was also observed when the wind was blowing towards the slope-side of the esker.

3.3. Time delay and diurnal variation

In the slab-on-grade house (A), the radon entry rate and also the indoor concentration of radon was observed to have a 2–3 h time delay. When this was taken into account in the linear regression analysis, it increased the coefficient of determination from 53 to 63% (see Fig. 3a). The corresponding coefficient for all variables increased from 57 to 66%. Arvela et al. (1988) reported a time delay using a prediction model for indoor radon. According to their model, a time delay of 1–4 h occurs between the diurnal extremes of temperature and radon concentration [11].

In addition to time delay, the variation in diurnal rate of radon entry was high with a constant temperature difference (Fig. 4). Furthermore, the average indoor concentration of radon was lower in the evening (165 Bq m^{-3}), when the difference in indoor–outdoor temperature was increasing than in the morning (222 Bq m^{-3}), when the difference in indoor–outdoor temperature was decreasing. Between 7 and 9 a.m. the radon entry rate, when adjusted by analysis of covariance to include all covariates and factors, was 25% higher and between 10 and 12 p.m., 20% lower than the average of measured rate of radon entry (85 Bq m^{-3} h^{-1}) (Fig. 5). In the analysis of covariance the main effect of factors and effects of covariates were statistically significant ($p < 0.000$).

The time delay was induced mainly by the slow change in indoor concentration of radon caused by the diurnal change in natural ventilation rate (temperature difference 12.7°C, SD 6.9°C) and partly by the technique used for radon measurement. The time delay may also have been induced by a crack in the rock, which acted as a limited radon source beneath the gravel layer.



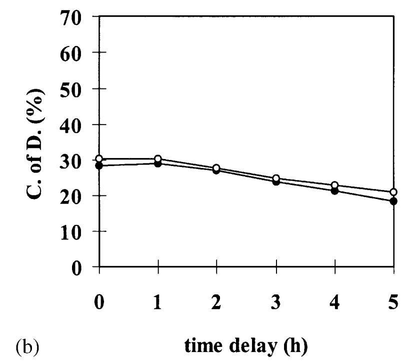


Fig. 3. (a) Dependence of coefficient of determination (C of D) on time delay in the slab-on-grade house A. The solid symbol line is the analysed with the best variable and the hollow symbol with all variables. n=3616 h. (b) Dependence of coefficient of determination (C of D) on time delay in the basement house B. The solid symbol line is the analysed with the best variable and the hollow symbol with all variables. $n = 1131$ h.

In the basement house (B), diurnal variations in the rate of radon entry were negligible, and there was no observed time delay in the rate of radon entry (see Fig. 3b). This may be due to the small and irregular variation in the measured temperature difference (mean 29.4°C, SD 4.3°C, see Table 1) and the observed sensitivity of radon entry to the effect of wind.

3.4. Effect of rain

In house B, it was not possible to study the effect of rain because the measurements were conducted during the cold winter months. The immediate effect of rain on radon entry was studied after ground frost had melted around the house A. Rain had no clear effect on the rate of radon entry. Before rain, during rain and after rain the group averages were lower than the average, including the time without rain. This was explained by the smaller difference in indoor–outdoor temperature. The rates of radon entry after the rainy period, when adjusted by analysis of covariance, were slightly higher (about 5%) than the average for the whole study

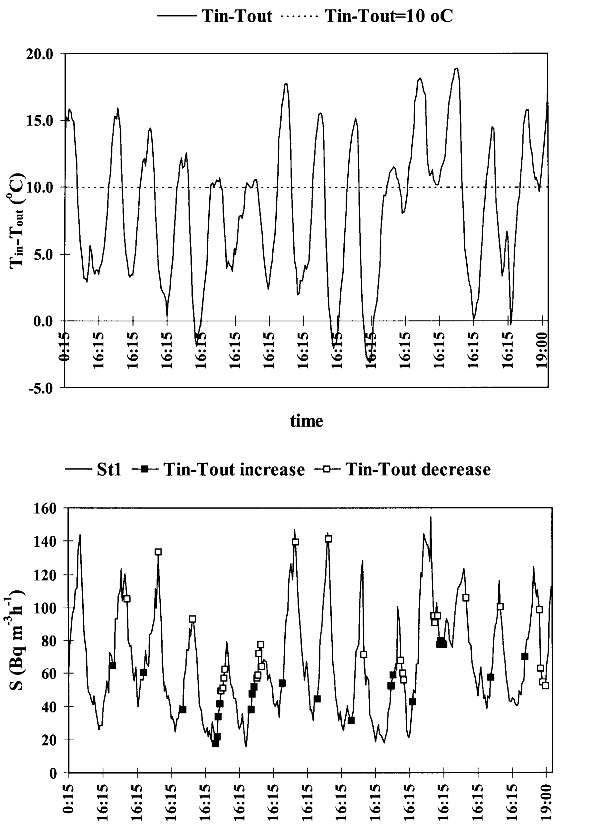


Fig. 4. Variation in diurnal rate of radon entry S (Bq m^{-3} h^{-1}) with a constant temperature difference ($T_{\text{in}} - T_{\text{out}} = 10^{\circ}$C) in the slab-on-grade house A. Measured time delay was 2.8 h in this period.

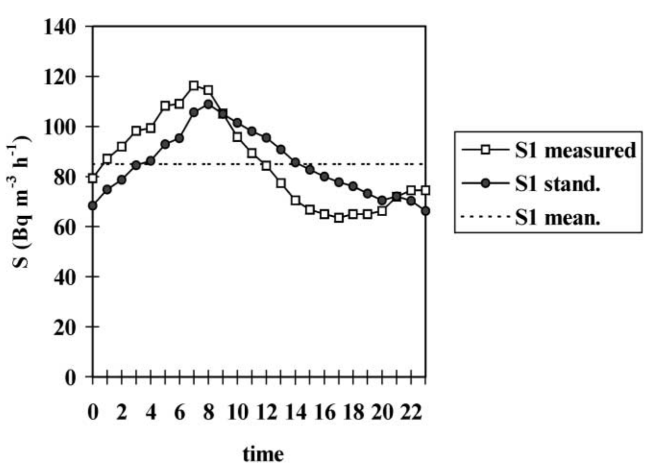


Fig. 5. Dependence of measured rate of radon entry S (Bq m^{-3} h^{-1}) throughout the day in the slab-on-grade house A. Analysed by analysis of covariance.

period (Fig. 6). In the analysis of covariance, the main effect of factors and effects of covariates were statistically significant ($p < 0.000$) and the coefficient of determination was 67%. The increasing of the rates of radon entry after the rain, when standardized by analysis of covariance, were

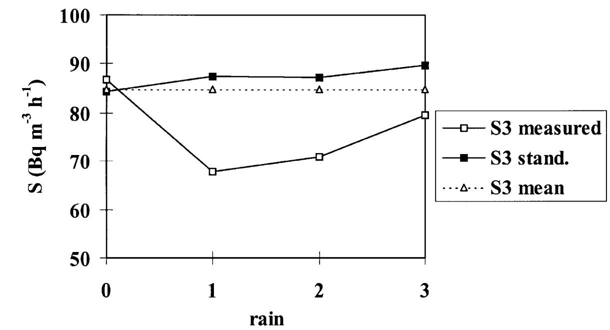


Fig. 6. Dependence of measured rate of radon entry S (Bq m^{-3} h^{-1}) on rain in the slab-on-grade house A. Measurements: 0 = no rain, 1 = before rain, 2 = rain and 3 = after rain. Analysed by analysis of covariance.

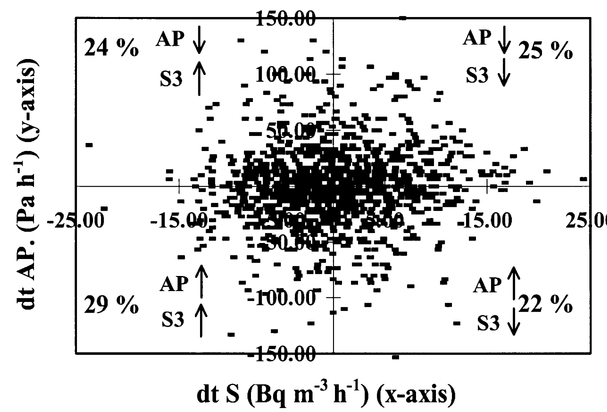


Fig. 7. Dependence of measured rate of radon entry dt S (Bq m^{-3} h^{-1}) on changes in barometric pressure dt AP (Pa n^{-1}) in the slab-on-grade house A. $n = 1195$ 3 h measurement interval.

small with respect to size of the coefficient of determination and correction of the radon entry.

3.5. Effect of barometric pressure

The effect of barometric pressure on the rate of radon entry has not been well characterized, and the research results have been partly conflicting. In this multiple regression analysis, changes in barometric pressure did not affect the rate of radon entry. Changes in barometric pressure were not found to be a significant variable in the rate of radon entry into either house. In the basement house (B), the regression coefficient was -0.033 ($p = 0.024$). A reduction in the barometric pressure increased rate of radon entry slightly, but for all variables the coefficient of determination was only 13%. The small coefficient of determination resulted from a very few measurement intervals (averaging 3 h) for weather observations. The graphic analysis (Fig. 7) in the slab-on-grade house (A) indicated that only 46% of all data were in those areas in where the reduction of barometric pressure increased the rate of radon entry (dt AP is positive

Table 2
Radon concentration (mean values of hourly, weekly and monthly measurements) ratios, standard deviation and correlation coefficients of radon concentrations in the individual rooms with each other rooms in the slab-on-grade house (A) and basement house (B)

House A	Correlation coefficient between different rooms	Radon concentration ration/ standard deviation	n
First period			
Living-room/bedroom	0.87	0.89/0.16	304 h
Second period			
Bathroom/living-room	0.81	0.89/0.24	374 h
Third period			
Living-room/bedroom	0.78	1.20/0.52	669 h
All week periods			
Living-room/bed room	0.91	0.83/0.09	Eight 1-week periods Four 2-week periods
House B			
All month periods			
Upstairs bedroom/ basement	0.65	0.95/0.40	Four 1-month periods
All month periods			
Upstairs living-room/ basement	0.37	0.77/0.18	Four 1-month periods

and dt S is negative) and a rise in barometric pressure decreased the rate of radon entry (dt AP is negative and S is positive).

The importance of changes of barometric pressure for the rate of radon entry cannot be very great because the diurnal variation in barometric pressure in the vicinity of both houses was irregular with the 3 h measurement interval.

3.6. Radon in individual rooms

In house A, radon concentrations were measured simultaneously (1 h average and weekly average) in individual rooms; living room, bedroom, and bathroom. Radon concentration ratios and correlation coefficients of individual rooms are shown in Table 2. The variation in radon concentrations in the individual rooms was simultaneous. In addition, the parallel and simultaneous radon concentrations correlated well with each other ($r = 0.78$–0.91), indicating that house A acted as a single zone. The maximum values for radon concentration were found at night in the bedroom. This was caused by the closing of the doors of the bedroom and possibly greater radon entry into the bedroom due to the crack in the rock, as a radon source beneath the bedroom. Unexpectedly, radon concentration in the living-room was higher than in the depressurised bathroom. The explanation for this may be the dilution of the infiltration air through the bathroom structures (n_{50} is 18 h^{-1}) and also high rate of air exchange (roughly n is 3 h^{-1}), in which case the possible increase in radon concentration in the bathroom remained small.

Similarly, in the basement house (B), radon concentrations were measured simultaneously (1-month average) in individual rooms: upstairs living-room and bedroom and basement. Radon concentrations in individual rooms were not correlated with each other as well as in the slab-on-grade house (A). The radon concentrations were higher in the basement than upstairs (Table 2) although two storeys were connected by an open stairwell. The explanation this may have been better dilution caused by the supply air in the upstairs than in the basement.

4. Conclusions

According to this study, the pressure-generating mechanisms and characteristics of the building and soil might simultaneously affect the rate of radon entry and the coefficient of determination, which cannot be observed only by single factor. The effect of physical and meteorological factors on the radon entry rate in two houses, one with slab-on-grade (A) and the other with a basement (B), were very different.

In the case of the basement house (B), which is built on a permeable esker, the main factor is the fluctuating wind blowing towards the esker. This factor, together with the convective subterranean air-flow in the esker, affect the pressure difference across the structure under the ground, the flow of soil gas, and the radon concentration in soil pores. For this reason, the variable factors investigated in this study explained only a part of the rate of radon entry. In this house, the highest rate of radon entry and the highest coefficient of determination were observed when the wind was blowing perpendicularly towards the esker.

In the slab-on-grade house (A), fluctuating wind and convective subterranean air-flow in the esker have no significant effect because the house is located on a gently sloping rocky surface. Thus, movement of the wind through the top soil generally has only a limited effect on pressure conditions in the soil. In house A, the rate of radon entry was highest in windy conditions when the wind probably induced the transport of containing radon air from one room to another or beneath the slab.

In this study, it was also observed that time delay of rate of radon entry affected the coefficient of determination. According to the analysis of covariance, the rate of radon entry was lower in the evening, when the indoor–outdoor temperature difference was increasing, than in the morning, when the indoor–outdoor temperature difference was decreasing, and the differences in diurnal rate of radon entry were high. The influence of the adjustment of all covariates was small. Thus, in addition to time delay and the ventilation factor, in future studies attention should be paid to the concentration of gas in the soil and the pressure difference across the slab.

Our study has shown that changes in barometric pressure were found to affect the rate of radon entry only negligibly because the diurnal variation in the barometric pressure of both houses was irregular when measured with 3 h measurement intervals. Nor was rain observed to affect radon entry clearly in slab-on-grade house (A).

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III

Keskikuru, T., Kokotti, H., Lammi, S. and Kalliokoski, P.

How did wind affect the radon entry into seven detached houses.

In: Proceedings of Radon in the living environment 19-23 April 1999, 309-319.

IV

Keskikuru, T., Kokotti, H. and Kalliokoski, P.

Pressure differences in seven supply and exhaust ventilated houses.

Proceedings of Healthy Buildings 2000, 3, 91-97.

PRESSURE DIFFERENCES IN SEVEN SUPPLY AND EXHAUST VENTILATED HOUSES

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ABSTRACT

Continued measurements of pressure difference, ventilation, weather and indoor parameters including concentration of radon have been made in seven mechanically ventilated detached single family houses under normal living conditions. Pressure differences were measured continuously across the basement wall and, for the sake of comparison, also across the roof in attic space. Measurements revealed that mechanical ventilation maintained in average small pressurisation of 0.3 Pa relative to outdoors and 0.7 Pa relative to attic space in the rooms with supply air vents. Pressure difference between the rooms depended on the air tightness of the house and the area of the opening between supply and exhaust ventilated rooms. It seems that small pressurisation relative to outdoors is a general situation in the rooms provided with supply air vents only. The good indoor air conditions including radon reduction efficiently in the range of 20% to 70% were obtained due to efficient supply and exhaust ventilation used continuously when compared to the previous situation.

KEYWORDS: pressure difference, ventilation, air movement, remedial measure, radon, residential

INTRODUCTION

The difference in indoor-outdoor pressure of the building, pressure differences between zones and the tightness of the building affects indoor air quality. The building should be tight when the mechanical ventilation is utilised so that sufficient and controlled ventilation could be obtained to each zone. In addition to the unbalanced mechanical ventilation, the difference in indoor-outdoor pressure of the building is caused by stack effect and wind. According to national Finnish standards, the buildings should be maintained depressurised relative to outdoors to avoid moisture damages on the building envelope [1]. For this reason, the air flows need to be adjusted so that the total flow of supply air remains lower than the total exhaust flow. In general the air flows are adjusted so that the total flow of supply air in one storey house remains 20% (15%) lower than the total exhaust flow and in two storey 25%, respectively. In addition to this, the zones of the building where bad odour or moisture may appear should be depressurised relative to the clean zones. The building should be so tight that a negative pressure can be maintained even at the ceiling level, especially in the winter.

Soil gas and radon flow from the soil into the house through cracks of floor and wall depend on the pressure difference between indoor air and the soil under the floor. This difference follows generally the indoor-outdoor pressure difference, and radon entry increases with increasing negative indoor-outdoor pressure difference [2].

The purpose of this study was to follow the long term pressure differences at seven mechanically ventilated detached single family houses after ventilation changes done for radon mitigation. In addition to this, the improvement of the indoor air quality was studied with a long term concentration of radon measurements.

METHODS

Study building

The building studied were one family house. The two-story hillside house B (floor area 188 m^2) has a basement whose walls extend in part below the ground level. The single storey houses (A, C - F) were slab-on-grade houses (floor areas 118,128, 108, 108 and 150 m^2). The single storey house G (floor area 129 m^2) has a crawl-space. The foundation of all houses were made of porous light weight concrete blocks. The houses were covered with bricks, load-bearing wall of houses were build of timber and the houses have a valley roof and open attic space.

Remedial actions

The original exhaust ventilation (house B and G) and combined exhaust and supply ventilation with kitchen fan (house A and C - F) were removed and all seven houses were equipped with mechanical supply and exhaust ventilation systems with a heat recovery. Fresh air was introduced into a bedrooms, a study room, a dining room, a kitchen and a living room through supply vents. The airflow was led from rooms with less moisture sources through gaps under doors (area should be ≥160 cm^2) to rooms where moisture was produced. Air was exhausted from the main moisture producing areas (a bathroom, a sauna, a toilet and a store room) through exhaust vents. According to national Finnish standards, the buildings should be a little depressurised relative to outdoors to avoid moisture damages on building envelope. For this reason, the air flows were adjusted so that the total flow of supply air was 15% - 25% lower than the total exhaust flow when the minimum air-exchange rate was obtained.

Monitoring and measurements

A data collection system was used for continuous monitoring of the parameters. The parameters were monitored under normal living conditions. The measurements after the remedial actions were conducted in house A from March to August 1993, in houses B - F from October 1993 to May 1994, and in house G the study lasted from March 1998 to February 1999.

Temperature and local wind speed/direction. The temperature of the living space was measured in the living room at height of 1.1 m above the floor. Local wind speed/direction and outdoor temperature were measured by means of a weather station at 2 m above the house roof ridge.

Pressure difference. The difference in indoor-outdoor pressure was measured with a low differential pressure transducer (SETRA 264, range is ± 25 Pa with accuracy of <±1% from full scale). The indoor pressure was measured at 0.25 m above the floor in the supply ventilated living room and the outdoor pressure was measured at the same height at the external wall. The low pressure differences are difficult to measure accurately because the result depends on the location of the measuring point at the wall and on the direction of the wind. For comparison the pressure difference was measured also in an open attic space which abated the effect of the wind fluctuations well in Finnish study [3] and [4].

Mechanical supply and exhaust flow rates (mechanical air-exchange rate) of air through main ducts were measured with devices of flow rate of air volume (Halton MSD, accuracy of the measurement <5%) which were based on pressure difference caused by air flow. The measurement device was connected to a pressure transducer (SETRA 264, range is 125 Pa with accuracy of <±1% from full scale).

Internal air flows and infiltration were measured in house E and F by using an integrating tracer gas method [5] and developed in Helsinki University of Technology [6]. Whit this passive tracer gas method (PFT) three different perfluoro-carbon type were used as tracers: methylcyclohexane (PMCH), methylcyclopentane (PMCP) and dimethylcyclohexane (PDCH) - one in each ventilation zone. In addition to the PFT-measurements , mechanical supply and exhaust flow rates were also determined simultaneously during the PFT-measurement.

Radon. A long term concentration of radon was measured in the same rooms as the short-term measurements. The long term radon determined by using alpha track detectors. The detectors were analysed by nuclear track dosimeters at the Finnish Centre for Radiation Nuclear Safety (STUK). The analyse method based on a German system and was modified for the STUK [7].

The tightness of the house was determined using the blow-door depressurisation test. The negative pressure was increased in step until 50 Pa [8].

RESULTS

Pressure difference.

The mechanical supply and exhaust air flows were adjusted so that the total flow of supply air was 15% lower than the total exhaust flow in one storey house (A, C - F) and 25% lower in two storey house (B). However, measurements revealed that mechanical ventilation maintained small pressurisation relative to outdoors and attic space in the rooms with supply air vents (living room, bedroom etc.) despite the negative pressure caused by the wind and thermal stack effect under winter conditions (Table 1). In four comparable houses (A, B , D and E) the mean value of the pressure difference across the wall was 0.3 Pa and across the roof in open attic space 0.7 Pa, respectively. The pressure differences across the roof were higher because the natural ventilated attic space abated the effect of the fluctuation of wind speed and direction. This has also earlier been shown experimentally by different authors [3] and [4]. The pressure difference was lower in a leaky house A than in tight houses B - F. In addition, the pressure difference was the highest in the house F which had not satisfactory area (≅100 cm^2) of the gaps and the lowest in the house G which had large openings (≅200 cm^2) under doors of supply and exhaust ventilated rooms.

At the beginning of the first measuring period, the total flows of supply and exhaust air were measured with accurate devices of flow rate of air volume. According the measurements of air flow in ventilation ducts, the difference in flow of supply and exhaust air did not follow the standard (Table 1). In house A, the average flow of supply air was 11% lower than the exhaust flow and thus, the difference was the closest to the standard in house A. On the other hand, the average flow of supply air was higher than the exhaust flow in houses E and F. It seemed that the total flow of ventilation was difficult to adjust accurately and a special attention, therefore, must be paid to more accurate devices of flow rate of air volume and adjusting methods. Otherwise as previous houses, in house G, the total flows of supply and exhaust air were adjusted at first so that the total flow of supply and exhaust air was balanced when at least a minimum air-exchange rate was obtained. Secondly the supply and exhaust flows were adjusted by using measurements of the pressure difference so that ventilation maintained a slight negative pressure of 0 - 0.2 Pa relative to outdoors. Because of the cold weather conditions, the difference in indoor-outdoor pressure was caused by a temperature difference although the ventilation was balanced.

Internal air flows and infiltration

The total ventilation rate and the internal air flows between zones were determined by using PFT-measurements. According to these tracer gas and mechanical ventilation measurements, the flow of supply air from rooms provided with the gap under door to the bathroom having the exhaust vent was only 65% in house E and 40% in house F. The rest of the supply air infiltrated indoors through the bathroom walls and ceiling. In addition, slightly pressurised rooms having supply air vents air also exfiltrated markedly outdoors. Between the different rooms with supply air vents (living room, bedroom etc.) the almost perfect mixing dominated when the doors were open most of the time. The relation of the transferred air flows between the bedroom and living room was 1.3 in the house E and 2.0 in the house F. The transferred air flow from the bedroom to the living room was higher than flow in opposite direction in both houses. The transferred air flow from the depressurised bathroom to the adjacent supply ventilated rooms occurred only in connection with the opening of the door.

Radon

Long term concentrations of radon were measured before and after ventilation improvement in order to evaluate the effectiveness of radon reduction. The concentrations of indoor radon were measured in the coldest winter time during the time between November to April. According to these measurements, the continuous and efficient use of the ventilation was found to be the most important factor to control indoor radon on the ventilation (Table 1). However, the precondition for the continuous use of the ventilation was the sufficient sound attenuation of the system of the ventilation.

Table 1. The table gives mean values of hourly measurements of difference in indoor-outdoor pressure (PD_{in-out}), difference in indoor-attic space pressure ($PD_{in-attic\ space}$), difference in indoor-outdoor temperature (T_{in-out}), mechanical ventilation rate (Q), and wind speed (Ws). The number of measurements is given as long term concentration of indoor radon (Rn) and the airtightness (ACH_{50}). The measurement time n (day)is also given.

FACTORS	HOUSES						
	A	B	C	D	E	F	G
n (day)	67	29	8	26	14	13	27
PD_{in-out} (Pa)	-0.0	-0.0	-	0.4	1.0	-	-
$PD_{in-attic\ space}$ (Pa)	0.1	0.8	0.5	0.8	0.7	1,3	-0,6
Q (h^{-1})su./ex.	0.50/ 0.56	0.56/ 0.54	0.58/ 0.62	0,75/ 0,80	0.55/ 0.49 0.75±0.2[a]	0.55/ 0,35 1.1±0.2[a]	0.35/ -
T_{in-out} (°C)	11.7	28.3	22.0	27.1	21.8	15.2	19.2
Ws ($m.s^{-1}$)	0.5	1.2	0.9	0.9	1.5	1.0	1.1
ACH_{50} (h^{-1})	8.6	3.6	5.8	6.0	3.6	3.1	3.1
Initial condition[c] Rn (Bq m^{-3})	Natural 850 (24h/d)	Ex 2931 (0h/d)	Ex+Su 2780 (1h/d)	Ex+Su 1520 (4h/d)	Ex+Su 1020 (18h/d)	Ex+Su - -	-
Before mitigation[c] Rn (Bq m^{-3})	Ex+Su+CA 630 (24h/d)	Ex 3080 (0h/d)	Ex+Su 795 (24h/d)	Ex+Su 870 (24h/d)	Ex+Su 630 (24h/d)	Ex+Su 845 (24h/d)	-
After mitigation Rn (Bq m^{-3})	280 (24h/d)	980 (24h/d)	630 (24h/d)	660 (24h/d)	520 (24h/d)	260 (24h/d)	-
Remedial efficiency (%)[b]	55	68	21	24	17	69	-

[a] one week PFT-measurement in end of the period, [b] compared to the before mitigation
Ex+Su = old combined exhaust and supply ventilation with kitchen fan, CA = circulation air
[c] the long term measurements of indoor radon before the remedial actions were conducted in coldest winter time in house A –91/92 and -92/93, in houses B -87/88 and-91, in house C –87 and -87/88, in house D –86/87 and 87/88.

DISCUSSION AND CONCLUSIONS

Measurements revealed that mechanical ventilation maintained small pressurisation relative to outdoors and relative to attic-space in the rooms with supply air vents. Pressure differences across the roof were higher because the attic space abated the effect of the wind fluctuation as found out earlier [3 and 4]. The difference in indoor-outdoor pressure and the pressure difference between supply and exhaust ventilated rooms depended on the air tightness of the house and area of the gaps under door between supply and exhaust ventilated rooms and also correctly fitted flow capacity of the supply and exhaust fans. It seems that small pressurisation relative to outdoors is a general situation in the rooms with supply air vents only. On the other hand, this probably does not cause condensation problems if the moist spaces are adequately depressurised. In addition, this kind of arrangement is beneficial for radon control. The effect of the area of opening (gap in the lower part of door) can be used as radon mitigation method in the rooms with supply air vents (living room, bedroom etc.). On the other hand, the harmfully high pressure can form without a sufficient area of the opening and without direct rout of transferred air flow to the depressurised room. The use of circulation air reduced the dilution and also depressurised more the house and thus, the concentration of indoor radon remained high in the house A as reported by us earlier [9]. After the installation of the new ventilation system, the average concentration of radon decreased. The good indoor air conditions including radon reduction efficiently in the range of 20% to 70% were obtained with efficient supply and exhaust ventilation used continuously. The results showed that the careful planning and carrying out of the ventilation system have big significance to the ability of the ventilation to mitigate the indoor radon. However, it was difficult to reduce high concentration of indoor radon merely on the improvements of ventilation system and by increasing the effectiveness of ventilation.

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V

Keskikuru, T., Salo, J., Huttunen, P., Kokotti, H., Hyttinen, M., Halonen, R. and Vinha, J.

Radon, fungal spores and MVOCs reduction in crawl space house: A case study and crawl space development by hygrothermal modelling

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Radon, fungal spores and MVOCs reduction in crawl space house: A case study and crawl space development by hygrothermal modelling

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ABSTRACT

In this case study was to investigate how ventilation of the crawl space will influence on concentrations of radon, fungal spores and MVOCs in the crawl space and indoors of detached house. The crawl space pressurisation by exhaust air from indoors was successful to prevent the convective flow of radon from the soil, but it increased microbial growth in the crawl space. After installation of the supply and exhaust ventilation in the crawl-space and in the living space, the concentrations of fungal spores in the crawl space and also entry of radon and MVOCs into a house decreased.

A microbiologically safe crawl space was determined with hygrothermal simulation utilizing the Finnish Mould Growth Model and a two year examination period. The optional structures of the crawl space being depressurised with exhaust ventilation included an open base uncovered ground and various air-sealed closed structures. When mould growth of building materials was at medium resistant sensitivity class, mould was not observed during different air change rates in any of the examined structures. Open base uncovered gravel ground is a functional solution of a crawl space, only when there are no organic materials. The air-sealed ground structure is recommended build with concrete + insulation and when air exchange rate (ach) varied from 0.2 to 1 h^{-1}. A concrete ground in the crawl space having ach from 0.2 to 0.6 h^{-1} is also very effective. XPS insulation and plastic sheet covered ground are not recommendable due to their high mould index.

1. Introduction

In the Nordic countries, crawl spaces are typically outdoor air-ventilated. In older buildings, ventilation is often natural, but mechanical ventilation is quite common in newer buildings.

If the crawl space less than 0.8 m height, which is typical nowadays, the operation of the natural ventilation is often unsatisfactory. The flow of radon-bearing soil gas and entry of mould-like odours (MVOCs) from the crawl space depend on the difference in crawl space-indoor pressure and the leakage area between the crawl space and the house. According to the studies, a significant fraction of infiltration air can enter into the house via the crawl space [1–4], but the correlation between microbial concentrations in crawl space and indoors depends on the microbial species [3] and pressure difference across the structure [4]. Natural ventilation of crawl space has not been found to give greater than about 50% reduction of indoor radon in most cases [1].

Infiltration of airborne particles such as fungal spores and microbial metabolites from the crawl space is a more complex and less known process than radon and MVOCs. Secondary metabolites are expected to be present in airborne spores, and may thus occur in airborne dust and bioaerosols. The penetration of fungal spores is expected by Liu and Nazaroff to be a function of particle diameter, crack geometry, and pressure difference across the crack [5]. They have modelled particle penetration through uncomplicated cracks. Further studies are needed in real buildings, where exist cracks having different kind of surface and geometry. In addition, the size of spores varies a lot according to the species being between 1 µm–100 µm and the mean size of microbial spores increases during the activities [6,7].

In buildings with mechanical ventilation the pressure difference between indoor and outdoor is often in a range of 0–10 Pa, but pressures of up to several tens of pascals are possible for building with mere exhaust ventilation [8–10]. In general, the exhaust ventilation in crawl space with opening vents, maintains slight under pressure relative outdoor. Improving ventilation in the crawl space reduces the indoor radon concentration by less 60% on average [11].

In mechanical crawl space depressurisation systems, a fan is installed to exhaust crawl space air and to reduce its entry into the house. However, crawl space depressurisation increases the convective flow of

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radon-bearing or other soil gas, moisture from the soil and outdoor air into the crawl space. In addition to avoid mould growth in the crawl space structures the efficient disturbance of fresh air in the whole sphere of crawl space is important and often defective. Crawl space depressurisation has been found to give reduction of indoor radon in the range of 70%–96% [1].

In crawl space pressurisation systems, a fan is installed to blow outdoor air or indoor air into the crawl space. If pressurisation is successful, it prevents the most of the convective flow of radon-bearing and other gas from the soil. In addition, reduction of radon depends on the leakage area between the crawl space and the living space. If indoor air is used it raises the relative moisture and temperature of the crawl space and thus, promotes the microbial growth in structures of the crawl space. Crawl space pressurisation also increases air infiltration from the crawl space into the living space. Crawl space pressurisation has been found to give reduction of indoor radon in the range of 30%–80% [1].

Concentrations of the fungal spores and identifying genus level of fungal colonies are used to confirm or exclude the presence of possible mould growth and damages inside building structure and on a surface of the structure. Air sampling, building material or surface sampling methods have been used for the microbial analyses. However, the result of the microbiological analyse depends on the activity of the mould growth and on ambient conditions (nutrients, pH, humidity and temperature) [12].

The moisture output in the crawl space comes mostly from ground moisture evaporation and high moisture contents of ventilation air brought in from outside. Outdoor air-ventilated crawl spaces can prove problematic in the Nordic countries during summer, when outdoor air is warm and humid, and thus the absolute humidity of outdoor air is higher than that of the crawl space. In numerous studies of crawl spaces, long-term 70–90% relative humidity has been observed [13–17]. Different countries and region vary in climate, which should consider in design of the crawl space. The temperature in the crawl space is considerably lower than that of outdoor air due to cool earth and massive foundations cooling the crawl space. Thus, the warm and humid air from outside used for ventilation is cooled in the crawl space and the relative humidity increases. According to Matilainen and Kurnitski [13,22], humidity problems in crawl spaces can be reduced by heat insulation the cold ground in the crawl space and by arranging basic ventilation 0.5–1 h-1. In cases where the bottom of the crawl space is covered by a layer of crushed gravel as a form of evaporation insulation, it is recommended that in summer ventilation should increase to the value of (2-5 h-1) [13]. Because there is always enough organic material in a crawl space for mould to feed on, the conditions are favorable for the start of mould growth [18,19]. Of used construction materials only freshly made concrete has a high pH level that makes it less likely to mould, but as it ages its resistance to mould reduces. Moulds are able to grow in broad temperature ranges, and only the relative humidity in crawl space conditions is the limiting factor for mould growth. At low temperature (5 °C) mould growth is limited and mould does not growth at temperature below 0 °C [21].

Generally, 75–80% can be considered a safe limit value for relative humidity in crawl spaces [14,20]. Some moulds can tolerate very low humidity, which from a microbiology perspective means that it is not possible to build a completely microbial clean crawl space. Mould growth on and the risk of moulding for structures in a crawl space can be assessed with a calculation by observing the building materials' temperature and humidity data over the examination period and using a developed calculation models that includes a classification that describes the mould growth sensitivity of typical building materials [19,20]. For the purpose of this calculation, materials have been divided into classes on the basis of their mould growth sensitivity. The models are a tool to simulate the progress of mould and decline development under different conditions on the surfaces of structures.

The microbial volatile organic compounds (MVOCs) are formed due to the primary and secondary metabolism of fungi and bacteria [23]. More than 200 compounds have been considered to be released by the microbes according to the literature [23]. However, those compounds can be released from the other sources as well. For example from the building and decoration materials, plants, chemicals and detergents. Nonetheless, many alcohols and ketones have a mould-like odour and are considered to be release from the microbes [24–26]. MVOCs can be analysed accurately, but the result of the analysis also depends on the activity variation of the mould growth and on availability of nutrients in a substrate. Furthermore, it is proposed that the different microbial species produce specific MVOCs, which could be used as an indicator of the microbial growth [24,26]. Korpi et al. [27] recently reported that some alcohols, ketones, and terpenes can be regarded as MVOC. On the other hand, the various VOCs accompany microbial activity but no single VOC is reliable indicator of biocontamination in building materials. Pasanen et al. [28] calculated theoretically indoor air concentration of selected VOCs for rooms with and without microbial contamination. The results revealed that microbial growth in construction seems to have only a marginal effect on the total VOC load in indoor air.

Aim of this case study was to investigate how ventilation parameters of the crawl space will influence on concentrations of radon, fungal spores and MVOCs in the crawl space and indoors. In addition to this, simulations were used to study the temperature and humidity conditions and mould growth sensitivity of crawl spaces. The open and closed ground structures were modelled during period consisting of consecutive building physically critical test years. The optimal ventilation rate of mechanical exhaust was determined in the crawl space for different structural options. The goal of mechanical ventilation is to maintain a sufficient pressure difference between the crawl space and living space.

2. Materials and methods

2.1. The studied building

The research building is a single storey one-family house (floor area 129 m^2) which was located in Tampere on the low-lying clayey soil. Under the floor, which was constructed from low density aerated concrete, there was a crawl space. There was a plastic membrane on the surface of bearing soil and a layer of sand (Fig. 1).

The house had an exhaust ventilation system that was used also for radon mitigation. In this ventilation system, indoor air was blown to the crawl space (volume 52 m^3) by the exhaust fan and air was then let to escape outdoors through an open duct through the roof. During the monitored periods, the house was inhabited by two adults and two children. Inhabitants did not use ventilation through the windows during the measuring periods.

2.2. Method for mitigation

The original pressurisation system was removed and the house was

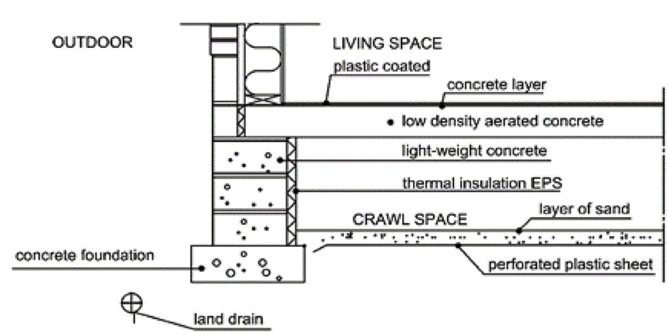

Fig. 1. The sectional drawing of the crawl space foundation in the studied building.

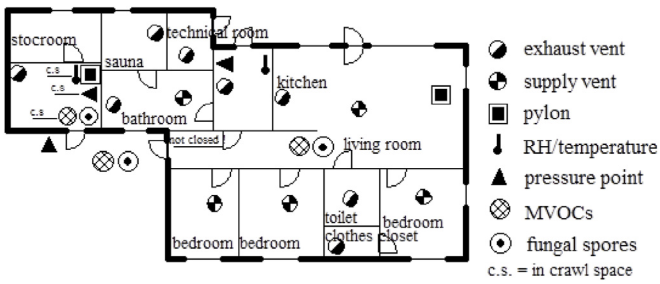

Fig. 2. Floor plan and sampling points of the crawl space in the studied building.

equipped with supply and exhaust system with heat recovery (Fig. 2).

The crawl space was equipped with a separate two-way mechanical ventilation with ducts in the crawl space. An exhaust fan was mounted to blow the crawl space air outdoors and a supply fan was installed to blow outdoor air into the crawl space. The heater (1,2 kW) was installed in the supply duct to prevent freezing of the crawl space. Air flows were adjusted to maintain a small under pressure in the crawl space relative to indoors to reduce the crawl space air infiltration into the living space and to minimise flow of radon-bearing gas and moisture from the soil into the crawl space. We have earlier [29] found that when the indoor-outdoor pressure difference is adjusted slightly positive by combined mechanical ventilation arrangement, the concentration of indoor radon in slab-on-grade house could be minimized. In addition, the influence of various factors on the rate of radon entry were investigated statistically in different types and location houses [30]. According to this study, the effect of the wind speed on the rate of radon entry was difficult to foresee because the effect of the wind on soil depended strongly on the wind direction, location of the houses and especially the permeability of the soil.

2.3. Crawl space modelling

In this study, the simulation capabilities of COMSOL Multiphysica [31] were used to perform crawl space temperature and relative humidity calculations over a period of two years. The parameter in the modelling was a pressure of 10 Pa less in the crawl space than in the living space was obtained by exhaust ventilation, which prevents harmful air leakage from the crawl space to the living space. The air-tightness of the crawl space's ground can be improved by selecting gravel or by sealing the ground with an airtight structure such as evaporation and heat insulation or by surfacing it with concrete. Harmful substances from the ground into the crawl space will decrease as the air-tightness of the crawl space improves. At the same time, the needed air exchange and depressurisation of the crawl space, will decrease.

On the basis of the simulation model's calculation results, the mould growth risk of the crawl space was evaluated with the experimental Finnish Mould Growth Model developed by VTT Technical Research Centre of Finland Ltd and the Tampere University of Technology. The model is a tool to simulate the progress of mould and decay development under varying conditions on the surfaces of structures. Mould growth was defined in this study according to a previously developed mould index classification [32]. Mould growth is presented in the form of a mould index that may have values between 0 and 6, and it is calculated from the changing temperature and humidity conditions.

Table 1 presents the mould index classification criteria. A classification depicting the mould growth sensitivity of the most common building materials having values between 1 and 4 (Table 2) has been integrated into the model.

Simulated outdoor temperature changes based on test year climate data Jokioinen Finland 2004 [34]. During the test year in question, the weather conditions were clearly more favorable than normally for mould growth and for the condensation of moisture into structures. The

Table 1
Mould index for experiments and modelling of mould growth on building materials [33].

Mould Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stage of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10–50% coverage, or < 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage approximately 100%

A safe limit value for a calculated crawl space mould index is a value of < 1 [21].

Table 2
Mould growth sensitivity classes and some corresponding materials in research [21].

Sensitivity Class	Materials
1 Very Sensitive	Pine sapwood
2 Sensitive	Glued wooden boards, PUR with paper surface, spruce
3 Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
4 Resistant	PUR with polished surface

test year is suitable for external envelope of building whose assemblies is protected from rain and the operation of the envelope is mainly influenced by relative humidity of outdoors [35]. With regard to mould growth, the target was that for only 10% of the years over a period of 30 years are more critical than the moisture reference test year [36].

The simulation was carried out for two crawl space structures (A and B), which are shown in Fig. 3 (Fig. 3). The first structure, A, is typical in Finland. The bottom of the crawl space is covered with a layer of air-permeable gravel. The observations were made with two aggregate gravel permeability values 1×10^{-8} (m^2) and 1×10^{-9} (m^2). The permeability values for gravel used in Finnish foundation structures are usually between 1×10^{-7} (m^2) and 1×10^{-9} (m^2).

The structures B1, B2, B3 and B4, comprise an air-tight crawl space ground, which prevents convective air flow via the gravel caused by depressurisation (Fig. 3). For the comparison, the different options for an insulating ground structure were concrete (5 cm), concrete (5 cm) + rigid expanded polystyrene XPS-insulation (7 cm), insulation on the surface of the ground (7 cm) and a plastic sheet on the surface of the ground. The simulation assumed that the perimeter gap between the footer and the ground cover was air-tight. The surface of the filling gravel of the crawl space was under ground level, which is typical in the Finnish crawl spaces.

Two mould growth sensitivity classes were used in the assessment of mould risk: a very sensitive SC1 and medium resistant SC3. Mould growth SC1 presents a structure that contains organic materials or e.g. the surface of a stone structure where organic dust has been collected [18]. Mould growth SC3 presents materials that do not mould easily, which in this study comprised concrete and heat insulation. The different mould sensitivity classes are presented in Table 1.

The convective flow field for a gravel filled ground structure was simulated with a 2D model. The effect of the corners of the building on the flow field's volumetric flow rate was assessed with a 3D model. Heat and moisture simulations were performed with a 2D model. Modelled heat, air and moisture transfers are shown in Fig. 4. The more detailed content of this study's heat and moisture transport modelling is presented by Salo et al. [37].

Outdoor air was brought through valves in the crawl space's socle. The crawl space has mechanical exhaust ventilation. In calculation

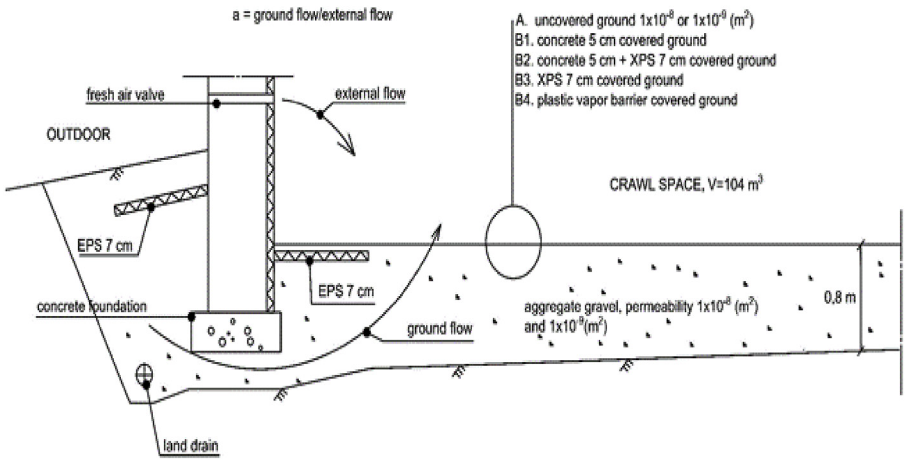

Fig. 3. Sectional drawing of the simulated crawl space foundation and different covers.

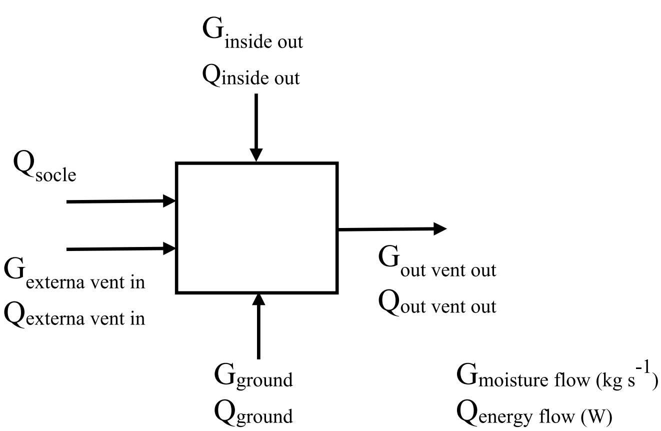

Fig. 4. Modelled heat and moisture transfers in crawl spaces.

observations the crawl space's air change and the size of the hold in the socle's valve were altered so that the crawl space had a depressurised pressure of −10 Pa. Calculations for open ground structures, the proportion of ground air flow in the crawl space and the external flow through the socle was adjusted (Fig. 4). In the simulations, the proportions were changed by adjusting the air flow of the socle's valves. In the simulations the ratio between ground and external flows (a) varied from 0.02 to 4.8. The freezing of the ground surface outside was not taken into consideration. The effect of freezing is not significant due to the thin frozen layer on the ground surface. The modelling surface was alternatively covered by expanded polystyrene (EPS).

2.4. Instrumentation of the case study

Data collection system was used to continuous monitor of the parameters, which are given in Table 3.

The indoor pressure was measured 0.25 m above the floor beside utility room (Fig. 2) and outdoor pressure was measured at the same height at the external wall.

Mechanical supply and exhaust flow rates of air through main ducts were measured with measurement devices of flow rate of air volume with accuracy of the measurement < 5%. The flow of crawl space air into the living space was investigated using tracer gas test (Brüel&Kjaer, type 7620). The tracer gas was injected into the exhaust air duct upstream of the exhaust fan where the tracer gas mixed exhaust air which was blown to the crawl space The concentrations of nitrous oxide (N_2O) were monitored downstream of the exhaust fan, in the crawl space and in the living space.

Local wind speed/direction and temperature were measured by means of a weather station. Wind direction and 1 h averages were calculated by using Yamartino method [40].

The tightness of the house was determined using the blower door depressurisation test. The negative pressure was increased in step until 50 Pa.

Viable microbes were collected by six cascade impactor (Andersen Inc.) from living room air, crawl space air and outdoors. The sampling rate was 28.3 l min^{-1} and the sampling time was 15 min. Viable fungal counts were determined by cultivation and total spore concentrations were counted and identified to a genus level with a light microscope by the Laboratory of Finnish Institute of Occupational Health. Concentrations were reported as cfu m^{-3}. Dichloran-18% glycerol agar (DG18) was used as a growth medium for xerophilic fungi, 2% malt extract agar (MEA) for mesophilic fungi and tryptone-yeast-glucose agar for actinomycetes. Culturable fungal and actinomycete concentrations, fungal genera, and total spore concentrations were determined from the material samples. The material samples were taken from light weight building slab in the middle of the crawl space. Culturable micro-organisms were determined by dilution plating on Dichloran-18% glycerol agar (DG18), 2% malt extract agar (MEA) and tryptone-yeast-glucose agar for actinomycetes. Fungal colonies were identified to genus level by a light microscope. The total spore concentrations were counted from the same dilutions as those used for the

Table 3
Monitored parameters and intervals of the case study.

Parameter	Measurement system	Measured interval (min)
Indoor temperature	Thermistor, 1.1 m above floor	60
Crawl space temperature	Thermistor, 0,4 m above ground	60
Outdoor temperature	Thermistor, in aspirated shield, 2 m above roof ridge	60
Difference in indoor-outdoor pressure	Pressure transducer ± 25 Pa with accuracy of < ± 1% from fs.	60
Difference in crawl space-indoor pressure	Pressure transducer ± 25 Pa with accuracy of < ± 0.25% from fs.	60
Indoor radon	Lucas scintillation cell [38] and Pylon AB-5 [39], 1.1 m above the floor and in the crawl space	60
Local wind speed and direction	Cup anemometer, 2 m above roof ridge	15/60

cultivation with a light microscope using a Fuchs-Rosendahl counting chamber. The microbial concentrations were expressed as spores per gram of dry mass of the material (cfu g^{-1}).

Microbially produced volatile organic compounds (MVOCs) were trapped on of Tenax GR absorbent with sampling rate of ca. 200 ml min^{-1}. Tenax samples were taken from crawl space and living room. In addition, reference samples were taken at the same time outdoors. Analyses of MVOCs were conducted by the Laboratory of Eastern University. Air samples were analysed by automatic thermo-desorption analyser (ATD400) combined with gas chromatography (HP-GC 6890) and a mass spectrometer (HP-MSD 5973). Analytical details have been published earlier [41,42]. Identification of compounds was accomplished by retention times, standards and GC-MS data library. MVOCs were analysed in selected ion monitoring (SIM) mode.1-chlorooctane (Fluka, > 98%) was used as internal standard, and other used standards in SIM mode analysis were: The alcohols 1-octanol (Merck, > 99%), 2-octanol (Merck, > 97%), 3-octanol (Merck, > 97%), *3-methyl-2-butanol (Aldrich, 98%), *3-methyl-1-butanol (J.T. Baker Chemicals B.V., > 98%), 1-octen-3-ol (Merck, > 97%), 2-ethyl-hexanol (Alfa Aesar, 99%); the ketones 2-pentanone (Fluka, > 99%), 2-hexanone (Merck, > 98%), 2-heptanone (Merck, > 98%) and 3-octanone (Fluka, 97%). In addition, geosmin (Sigma, > 98%), 2-methylfuran (Aldrich, 99%) and 3-methylanisole (Fluka, > 98%). Standards were made in methanol (Rathburn HPLC grade) and added to the Tenax GR tube. Standard tubes were analysed the same way as samples. Other volatile organic compounds were sampled and analysed the same ways as MVOCs except in GC-MS analysis was done in SCAN-mode. Used standards in SCAN mode analysis were alfa-pinene (Fluka, > 99%), limonene (Fluka, > 97%), alfa-terpinene (Fluka, 85–90%), toluene (Ronil ctd, > 99.9%), ethylbenzene (Merck, > 99%), nonane (Fluka, 99%), pentanale (Merck, > 98%), hexanale (Fluka, 99%), heptanale (Merck, > 97%), octanale (Merck, > 98%), and decanale (Merck, 97%).

*) Marked compounds are the most likely MVOCs, which probably do not have any other sources [27].

3. Result and discussion

3.1. Case study. Results before the changes in the ventilation

Before the installation of the new ventilation system the average concentration of radon in the crawl space was 340 Bq.m^{-3}, based on continuous measurements during four weeks (Table 4).

According to the tracer gas test and the measurements of air flow in ventilation duct, the ventilation rate (3/4 of full capacity) was only 0.34 h^{-1} (ach) and the house envelope was (ach_{50} = 3.1). That depressurised the house by 1.0 Pa relative to outdoors. Indoor air exhausted to the crawl space caused the crawl space to be pressurized by 3.7 Pa relative to indoors. The ventilation rate of the crawl space was 2.2 h^{-1}. The average temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the measuring period were 22.9 °C, −2.9 °C, 11.9 °C, 85% and 1.1 m s^{-1}, respectively. According to the tracer gas test, crawl space pressurisation caused that about 6 m^3 h^{-1} of the exhaust air infiltrated from crawl space back to the living space. Because of tight floor between the crawl space and living space, the infiltration was about 8% of exhaust flow. However, slightly high microbial concentrations were detected in the house, but only the radon concentration of 25 Bq m^{-3} indoors were caused by the flow from the crawl space.

The ratio of radon concentration between crawl space and indoor 13.5 was closed to the relation between the flow into the crawl space and leak flow back indoors 12.5. On the other hand, the ratio of MVOC concentration between crawl space and indoors was 0.5. The ratio between fungal spores in crawl space and indoors depends on microbial species, infiltration efficiency of different size spores and other microbial sources indoors.

The total crawl space concentration of mesophilic fungal spores was 10040 cfu m^{-3} in air and the total concentration of xerophilic fungal spores was 7852 cfu m^{-3}, because the conditions of microbial growth in the crawl space was favorable. The material samples were taken from light weight concrete slab in the middle of the crawl space. The total crawl space concentration of mesophilic fungal spores from the material sample was 61300 cfu g^{-1} and the total concentration of xerophilic fungal spores was 83800 cfu g^{-1}. In the material sample, the dominant specie was *Aspergillus* (90% of total species), the same which was analysed in air samples both in the crawl space and living space. The concentrations were high even though the visible growth on the subsurface of the slab was not noticed. Probably, fungal spores only attached on the subsurface of the slab and microbes grew mainly on the ground surface.

3.2. Case study. Results after changes in the ventilation

During the study period 2 the new supply and exhaust ventilation

Table 4
Results when exhaust air from indoors was blown into crawl space (period 1, pressurized crawl space) and when separate supply and exhaust ventilation systems were operated both in the crawl space and in house (period 2 and period 3). In addition, the exhaust flow of the crawl space was increased during period 3.

	Period 1, March to April		Period 2, October		Period 3, February	
	House	Crawl s.	House	Crawl s.	House	Crawl s.
Radon (Bq m^{-3})	25	340	20	755	22	767
ach (h^{-1})	0.34	2.2	0.34	2.2	–	3.2
Pressure diff. (Pa)	−1.0 (in-out)	+3.7 (c.s.-in)	−0.2 (in-out)	−2.7 (c.s.-in)	−1.2 (in-out)	−2.0 (c.s.-in)
Indoor temperature (°C)	+22.9	+11.9	+21.4	+12.3	+21.5	+7.2
Outdoor temperature (°C)	−2.9		+5.4		−2.3	
Wind speed (m s^{-1})	1.1		1.1		1.2	
RH (%)/abs. (g m^{-3})	–	85/9.1	38/7.1	90/9.6	28/5.3	87/6.9
Fungal spores indoors (cfu m^{-3})						
Mesophilic fungi	174	10040	288	3952	59	616
xerophilic fungi.	160	7850	336	2300	67	1087
Domianant species of total species (%)	*Asperg.* 77%	*Asperg.* 90%	*Cladosp.*79%	*Penicill.*79%	*Penicill.*44%	*Asperg.* 85%
Actinomycetes	–	2	–	7	–	–
MVOC (μg m^{-3})	83	44	56	5	40	8
[a]MVOC (metab.) (μg m^{-3})	9	7	13	2	1	0

[a] Marked compounds are the most likely MVOCs, which probably do not have any other sources [27].

was adjusted so that the ventilation maintained slight under pressure of 0.2 Pa relative to outdoors and the ventilation rate (1/3 of full capacity) of the house was 0.35 h^{-1} (Table 4). The new ventilation system of the crawl space was adjusted so that the ventilation maintained depressurisation of 2.7 Pa relative to indoors and the ventilation rate of crawl space was the same 2.2 h^{-1} as before the ventilation changes. The averages temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the first measuring period were +21.0 °C, 4.0 °C, 12.3 °C, 90% and 1.1 m s^{-1}, respectively. The radon concentration increased to value of 755 Bq m^{-3} due to increased depressurisation of the crawl space.

At the beginning of the last measuring period 3 the ventilation system of crawl space was readjusted. The averages temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the last measuring period were +21.5 °C, −2.3 °C, +7.2 °C, 87% and 1.2 m s^{-1}, respectively. After the increased exhaust ventilation rate, the average concentration of radon in the crawl space increased to 767 Bq m^{-3}, but average indoor concentration of radon even decreased slightly to 22 Bq m^{-3}, based on continuous measurements during two weeks. The difference in crawl space - outdoor pressure was the most significant variable ($p < 0.00$) according to the multiple regression analysis to explain the concentration of crawl space radon (Fig. 5).

The coefficient of determination (100 R^2) was 79% by the difference in crawl space - outdoor pressure. The coefficient of determination became only slightly higher for all variables, 80%. The variables were difference in indoor-outdoor temperature, difference in crawl space-outdoor pressure, wind speed and ventilation rate. Wind speed and the difference in indoor-outdoor temperature were significant variables ($p < 0.05$) but temperature difference and wind speed were not important variables for explain the concentration of crawl space radon. The wind had only a slight influence to the ventilation of the closed crawl space. In addition, wind speed was not found to influence the concentration of indoor radon although according to analysis of covariance the radon concentration was 12% more than grand mean in the crawl space when the wind came from shielded (houses, hills and trees) directions. In addition, the lowest concentration of radon in the crawl space was 13% less than grand mean when the wind blew from unshielded directions. Radon concentration in soil in vicinity of the house probably decreased during the wind. The influence of the crawl space ventilation was difficult to foresee because mechanical ventilation rate did not vary.

The new supply and exhaust ventilation maintained under pressure of 1.2 Pa in living space relative to outdoors, which is due to air leakage into crawl space and due to higher difference in indoor-outdoor temperature during the last period compared to the earlier period. In order to maintain a small negative pressure in the crawl space relative to

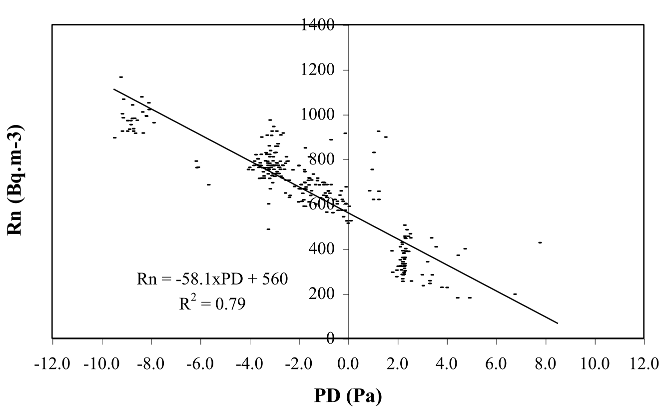

Fig. 5. Dependence of measured concentration of crawl space radon Rn (Bq m^{-3}) on difference in crawl space-outdoor pressure PD (Pa), based on 859 1 h average measurements during periods 1, 2 and 3.

indoors, the exhaust flow had to be increased during the cold weather condition at the beginning of the last measuring period. Thus, the crawl space was depressurised by 2.0 Pa relative to indoors. The ventilation rate of the crawl space was increased from 2.2 h^{-1} to 3.2 h^{-1}. The average radon concentration was doubled 767 Bq m^{-3} in the crawl space and stayed indoors at the same level 22 Bq m^{-3} during continuous measurements lasting two weeks. However, the negative pressure relative to the living space prevented successfully the flow of crawl space air into the living space. Unexpectedly, air moisture of the crawl space did not decrease immediately after changes in ventilation because the moisture capacity of the crawl space and soil is high and evaporation of the moisture is a slow process. However, the total concentration of mesophilic fungal spores in the crawl space decreased from 10040 cfu m^{-3} to 3952 cfu m^{-3} and after last measuring periods still more to 616 cfu m^{-3} after the installation of the new ventilation system. Similarly, the total concentration of xerophilic fungal spores decreased from 7852 cfu m^{-3} to 2300 cfu m^{-3} and finally to 1087 cfu m^{-3}. Also the dominant fungal genera changed after changes in the ventilation. Before changes in the ventilation the dominant species was *Aspergillus* (90% of total species) in the crawl space and indoors in the living room (77% of total species). After installation of the combined mechanical ventilation the dominant species was *Cladosporium* (79% of total species) and *Penicillium* (44% of total species) in the living spaces and *Penicillium* (79% of total species) and *Aspergillus* (85% of total species) in the crawl space. The change of the dominant species and total concentrations in the crawl space indicated that the conditions of microbial growth in the crawl space had changed. The temperature and relative humidity in the crawl space decreased in comparison between periods 2 and 3. At the same time air exchange rate increased by the value of 1 h^{-1} obtaining the more effective dilution of fungal spores.

The total concentration of MVOCs in the crawl space decreased as a result of the separate ventilation system. The concentrations of MVOC of specific microbial species decreased when the concentration of fungal spores decreased. The crawl space concentration of MVOC of specific microbial species was very low and also lower in the crawl space than in the living space in spite of the higher concentration of fungal spores in the crawl space than indoors.

It was difficult to adjust ventilation of the crawl space so that the ventilation maintained slight under pressure relative to indoors when the weather conditions changed. During the coldest weather conditions the difference in indoor-outdoor pressure was caused by temperature difference although the ventilation was in balanced. Maximum pressure differences under northern winter condition with flow balanced ventilation and no wind are −2 Pa and −4 Pa, calculated due to the thermal stack effect in a single story house and in a two-story house. The ventilation rate of the crawl space had to be increased, because a small under pressure in the crawl space relative to indoors had to exist to prevent infiltration of contaminants into the living space. In the winter the ventilation rate of the crawl space was high (3.2 h^{-1}) and for this reason the ventilation cooled the crawl space and slab and also increased the heat losses of the house. However, special attention should be paid when designing the ventilation and structure of the crawl space because cooling increases the relative humidity and condensation. On the other hand, in a tight crawl space the sufficient pressure difference will be obtained with a lower ventilation rate without cooling problem of the structures.

3.3. Results of crawl space modelling

The parameter for the calculation was a pressure of −10 Pa in the crawl space compared to the living space, which was assumed to be constant and to be maintained by correctly adjusted valves and flow rate of exhaust fan. The convective air flow via the ground depended on the permeability of gravel. More permeable gravel 1×10^{-8} (m^2) allowed the convective air flow via the ground caused by depressurisation

Table 5
Calculated air change rate (ach, h^{-1}) in a mechanically ventilated and depressurised crawl space based on the external and ground flow (m^3/s).

External flow ($m^3\ s^{-1}$)	ach (h^{-1})		
	Uncovered ground		Covered ground
	Permeability 1×10^{-8} (m^2)	Permeability 1×10^{-9} (m^2)	–
0.005	1.2	0.3	0.2
0.0115	1.4	0.5	0.4
0.0173	1.6	0.7	0.6
0.0230	1.8	0.9	0.8
0.0288	2.0	1.1	1
0.0576	3.0	2.1	2
0.144	6.0	5.1	5

to be $0.028\ m^3\ s^{-1}$, and similarly only $0.003\ m^3\ s^{-1}$ with less permeable gravel 1×10^{-9} (m^2). Also gravel materials that were coarser than 1×10^{-8} (m^2) were used in foundations. When permeability was 1×10^{-7} (m^2), the convective flow via the ground increased to the unreasonable value of $0.28\ dm^3\ s^{-1}$. Table 5 presents the values of the air change rate (ach) in the crawl space and of the external flow used in the simulation.

An open base structure's (Fig. 3) air change rate is greater than ach of sealed ground structure because soil gas flow is less in the sealed crawl space. The external air flow caused by the depressurisation (−10 Pa) of the crawl space during mould critical time dries up significantly as it travels via the soil to the crawl space; see the simulation result (Fig. 6). The phenomenon depends on the characteristics of gravel and air flow, and it would require more research.

The results for mould index for an open ground structure with two permeability values when the mould sensitivity classes of building materials are 1 and 3 are presented in Table 6 and at a permeability of 1×10^{-8} for gravel in Figs. 7 and 8.

The mould index for open ground structures increases at an earlier point in time at all air change rate values than the mould index for outdoor air. The temperature of the crawl space is lower than that of outdoor air, which means that outdoor air introduced to the crawl space cools causing arise in relative humidity and thus a higher mould index. The mould index is not dependent on the permeability values used in calculation, but only a bit on the air change rate in the crawl space. When the mould growth sensitivity class (SC) for building materials is 3 (concrete etc.) the structure is effective because the mould index remains under 1, and no mould growth is estimated to exist (Table 6, Fig. 7). Respectively, the structure is not recommended when the mould growth sensitivity class (SC) of building materials is 1 (e.g. pine sapwood), because the mould index rises over the permitted value of 1

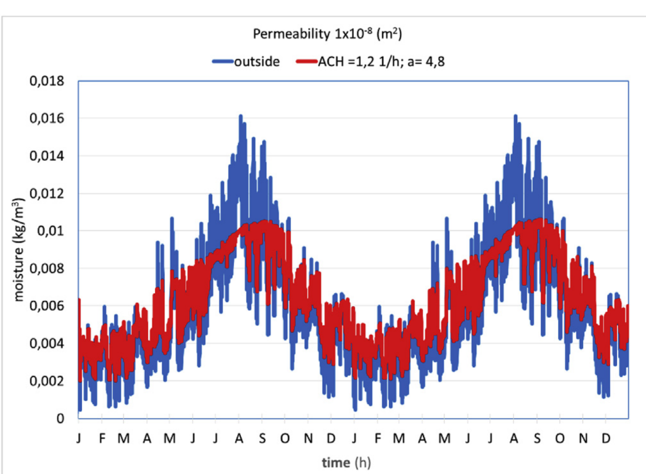

Fig. 6. Change in moisture content of external air flow ($m^3\ s^{-1}$) as it travels via the soil by convective flow to the crawl space. a = ground flow/external flow.

Table 6
Maximum value for the mould index of a crawl space with an open ground structure, when the SC of building materials is 1 and 3 and with two ground permeability values. Subscript"SC 1″ means mould growth sensitivity class 1 (very sensitive) and "SC 3" mould growth sensitivity class 3 (medium resistant).

Permeability 1×10^{-8} (m^2)								
ach (h^{-1})	1.2	1.4	1.6	1.8	2.0	3.0	6.0	outside
a = ground flow/ external flow	4.8	2.4	1.6	1.2	1.0	0.48	0.19	–
Mould Index, SC 1	**5.8**	**5.9**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	5.9
Mould Index, SC 3	0.31	0.34	0.36	0.37	0.36	033	0.26	0.19
Permeability 1×10^{-9} (m^2)								
ach (h^{-1})	0.3	0.5	0.7	0.9	1.1	2.1	5.1	outside
a = ground flow/ external flow	0.48	0.24	0.16	0.12	0.10	0.05	0.02	–
Mould Index, SC 1	**5.9**	**5.9**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	5.9
Mould Index, SC 3	0.35	0.37	0.40	0.37	0.37	0.32	0.25	0.19

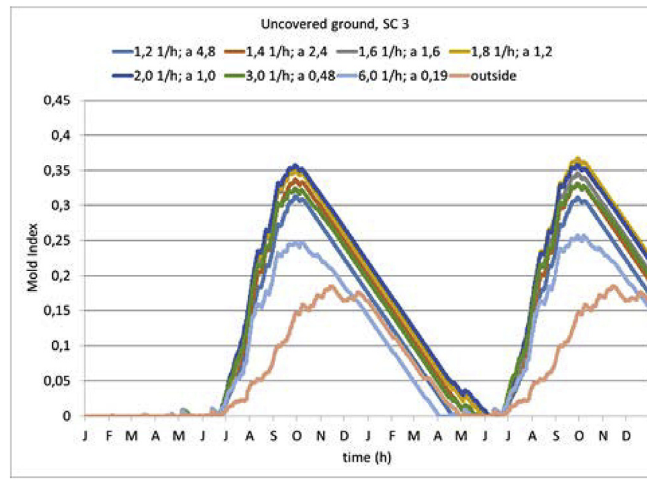

Fig. 7. Mould index on the gravel (permeable 1 × 10-8 m^2) surface of crawl space with mould sensitivity class of SC 3 during simulated conditions similar to those of the test year's climate.

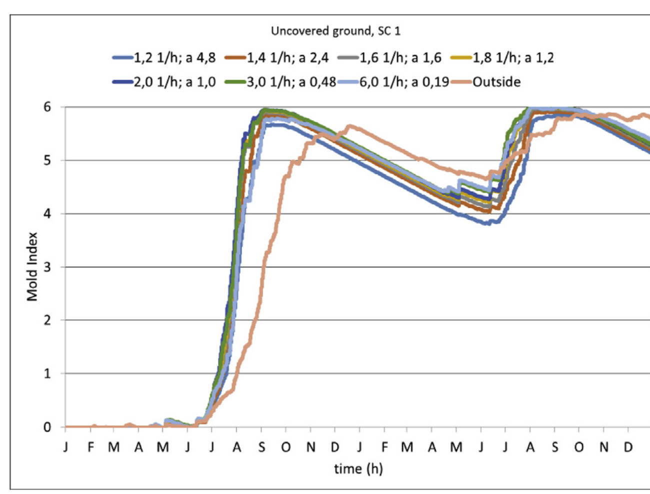

Fig. 8. Mould index on the gravel (permeable $1\times10^{-8}\ m^2$) surface of crawl space with mould sensitivity class of SC 1 during simulated conditions similar to those of the test year's climate.

Table 7
Maximum mould index values of a crawl space with an air-tight ground structure at SC 1 and 3. Subscript"SC 1″ means a mould growth sensitivity class of 1 (very sensitive) and "SC 3" a mould growth sensitivity class of 3 (medium resistant).

ach (h^{-1})		0.2	0.4	0.6	0.8	1.0	2.0	5.0	outside
Concrete 50 mm ground cover	SC1	0.15	0.59	**1.01**	**1.38**	**1.88**	**3.91**	**4.74**	5.87
	SC3	0.00	0.01	0.03	0.05	0.08	0.12	0.12	0.19
Concrete 50 mm + XPS insulation 70 mm cover	SC1	0.00	0.02	0.14	0.31	0.43	0.92	**1.75**	5.87
	SC3	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.19
XPS insulation 70 mm cover	SC1	**5.66**	**5.81**	**5.93**	**5.93**	**5.94**	**5.95**	**5.91**	5.87
	SC3	0.26	0.28	0.33	0.32	0.31	0.27	0.20	0.19
Plastic sheet cover	SC1	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	5.87
	SC3	0.61	0.57	0.52	0.47	0.44	0.35	0.27	0.19

(Table 6, Fig. 8).

In the air-tight crawl space convective air flow via the ground was prevented. For the purpose of the simulation, the ground structure used was alternatively concrete, concrete + insulation, and insulation and a plastic sheet (Fig. 3). The mould index values for crawl space building materials at SC 1 and 3 is presented in Table 7 (Table 7).

The mould index was less than 1 in all the simulations when air-sealed structures were used and the mould growth sensitivity class of building materials was 3. An increase in the mould index was only estimated when the air change rate increased as time passes in plastic covered ground crawl space. The plastic insulated ground structure (Fig. 9) obtained greater mould index than that of XPS insulated ground structure (Table 7). The mould index of plastic or XPS insulation covered ground structures with SC 3 decreases as the air change rate increases. When the mould growth sensitivity class of building materials in the crawl space is 1 (e.g.. pine sapwood) with a concrete surfaced ground structure, the mould index remained less 1 when air change rate was up to 0,6 h^{-1} (Fig. 10). The mould index exceeds the value of 1 with higher air change rates. The mould index for a ground structure built with concrete and XPS insulation with SC 1 was less than 1 when the air change rate did not exceed the value of 2 h^{-1} (Fig. 11). The low mould index of concrete structures is due to concrete's high moisture capacity; concrete absorbs excess moisture to itself and balances out changes in humidity.

Fig. 12 shows a comparison of the temperature in crawl spaces constructed with ground cover of concrete, concrete + XPS, XPS and plastic when the estimated air change rate was 0.6 h^{-1}. In summer period the temperature in a crawl space insulated with concrete or plastic was lower than in one which was sealed with XPS or

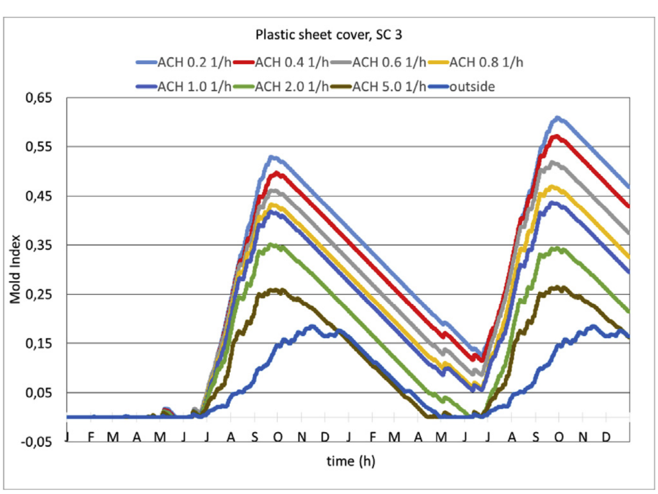

Fig. 9. The mould index of crawl spaces with plastic sheet covers with an SC 3 for building materials under simulated conditions similar to those of the test year's climate.

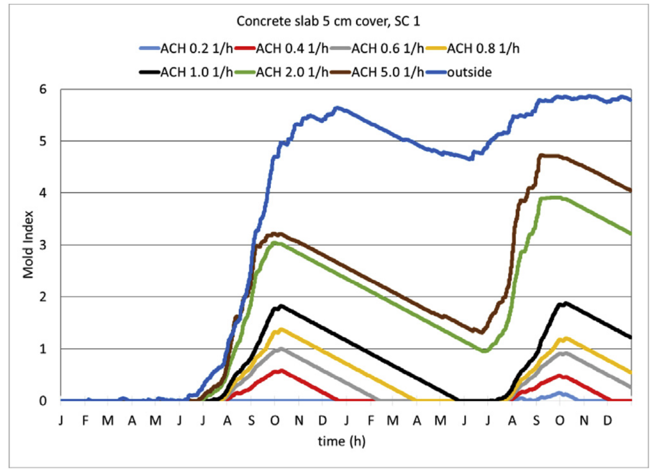

Fig. 10. The mould index in a concrete covered crawl space with an SC 1 for building materials under simulated conditions similar to those of the test year's climate.

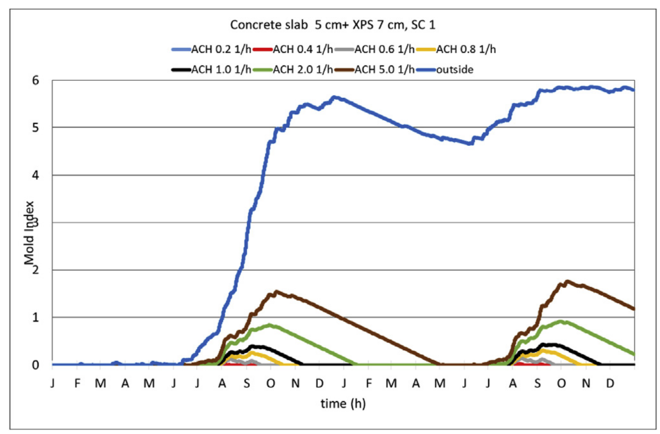

Fig. 11. The mould index in a crawl space with a concrete + XPS-insulate cover with an SC 1 for building materials under simulated conditions similar to those of the test year's climate.

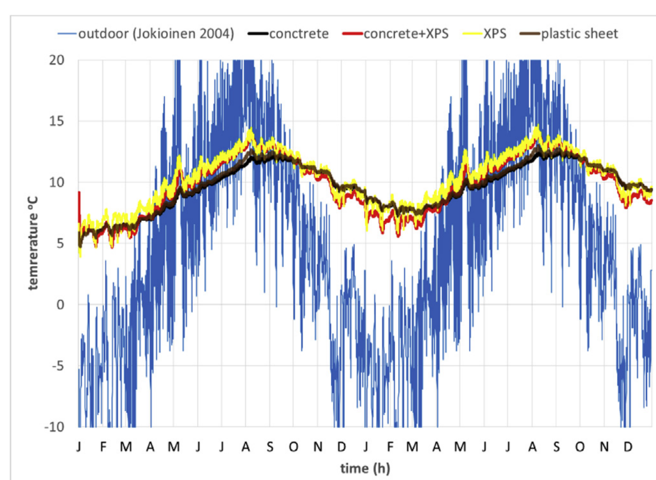

Fig. 12. Temperatures in the crawl space with different ground covers and an air change rate of 0,6 h^{-1}.

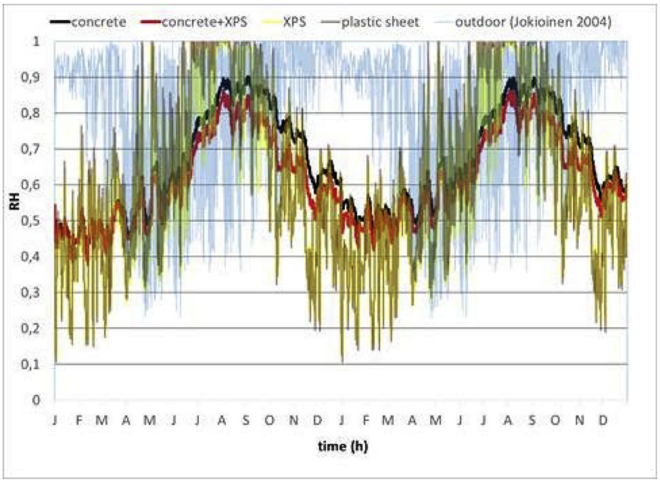

Fig. 13. The relative humidity (RH) in the crawl space with different ground covers and an air change rate of 0,6 h^{-1}.

concrete + XPS. In winter period the situation is the opposite.

Fig. 13 presents a comparison of the relative humidity of crawl spaces constructed with concrete, concrete + XPS, XPS and plastic when the estimated air change rate was 0.6 h^{-1}. During the examination period when the humidity of outdoor air was high, the relative humidity in a crawl space insulated with concrete was lower and the fluctuation was smaller than in one which was sealed with plastic or XPS.

The mould index exceeded the value of 1 with all air change rates when ground structures were constructed with XPS insulation or plastic and the mould growth sensitivity class of building materials was 1.

4. Conclusions

According to this case study, the crawl space pressurisation system with exhaust air from indoors was successful to prevent the convective flow of radon from the soil. However, high microbial concentrations were detected in the crawl space, because moist and warm air was blown into the space. This kind of crawl space pressurisation is effective in control of the indoor radon with certain qualifications; the slab has to be totally tight and organic materials should not exist in a filling soil and in structures of the crawl space. Carefully balanced separate two-way ventilation in the crawl-space and supply and exhaust ventilation in the living space and also tight slab between them appears to be beneficial to prevent the crawl space air infiltration into the living space.

In this study, the concentration of fungal spores and MVOC decreased as a result of the separate ventilation system in the crawl space during short follow-up periods. The crawl space concentration of MVOC of specific microbial species was very low and also lower in the crawl space than in the living space in spite of the higher concentration of fungal spores in the crawl space than indoors. These findings are consistent with the previous findings that microbial contaminated areas might not be verified by the MVOC measurements [23].

The air change rate of the crawl space which maintained under pressure relative to indoors was high in the winter and summer conditions. This should be noticed in design of the ventilation and structure of the crawl space, because in a tight crawl space the sufficient pressure difference will be obtained with a lower ventilation rate. Then cooling or high humidity problems of structures could be avoided. The tight solutions of the crawl space should be developed when reduced ventilation in the crawl space is designed. In summary, practical instructions, which are based on the research, would be needed on the ventilation and the structure solutions of the crawl space.

A microbiologically safe crawl space was determined with hygrothermal simulation utilizing the Finnish Mould Growth Model. The optional structures of the crawl space being depressurised 10 Pa relative to indoors to reduce air infiltration from the crawl space into the living space. According to the simulation, the recommendable air change rates depend on insulation of the crawl space, its structure and the mould growth sensitivity class of the materials. A crawl space with an open base uncovered ground (gravel) structure can be kept depressurised with moderate exhaust ventilation when the soil's permeability value is 1×10^{-9} and 1×10^{-8}. However, when permeability increases, the air change rate must be increased to achieve depressurisation. This causes excessive cooling of structures and building technology devices in the crawl space in winter. An open ground structure covered with gravel and depressurised with exhaust ventilation is an effective solution when the mould growth sensitivity class of used building materials is 3, and there are no organic substances in the crawl space. But the structure with the mould growth sensitivity class of building materials 1, is not effective for any air change rate.

The simulation assumed that the perimeter gap between the footer and the ground cover was air-tight. All the simulated structures for crawl space with an air-sealed ground structures in mould growth sensitivity class 3 were satisfactory with various exhaust air change rates. However, air change rates of over 2 h^{-1} caused too much cooling of the crawl space in winter and were not economically feasible. In mould growth sensitivity classes 1 the most recommended building material for ground structures was concrete + XPS insulation and the recommended air change rates are from 0.2 to 1 h^{-1}. The next most effective structure of the crawl space ground was concrete with no insulation and recommended air change rates are from 0.2 to 0.6 h^{-1}. Mould index rises if the air change rate exceeds the value of 0.6 h^{-1}. The low mould index of concrete structures is due to concrete's high moisture capacity; concrete absorbs excess moisture to itself and balances out changes in humidity. XPS insulation and a plastic-sealed ground structure are less effective options and these structures are not recommended due to their high mould index.

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